DAMAGE BOOK

The Social Relations of Science

by

J. G. Crowther

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"In history nothing is improvised, and here once more we can see how untrue it is that little causes lead to great results."

—H. PIRENNE, "A History of Europe."

PREFATORY NOTE

The present crisis of civilization shows that science is a determining factor in the destiny of mankind, so scientists and other members of the community have now the decisive responsibility of seeing that it is used for good and not for evil.

The beneficence of science has not been seriously doubted during the last three centuries, and the majority of scientists have plodded happily along with their problems, taking the justification of their work for granted.

The danger in this detachment has now become evident. Scientists and other responsible citizens must formulate a social policy for science. Some have repeated the view that science and scientists are above social conflict, and should pursue the promptings of curiosity without reference to contemporary affairs. The ease with which the exponents of this view have recently been brushed aside, ignored or exterminated shows that science will suffer severely unless its roots in social interest are consciously strengthened.

The creation of a durable social policy for science depends, therefore, on an understanding of the actual relations of science to society. These relations, and the nature of science itself, cannot be understood without an examination of how science came into existence. The elucidation of this problem is the first step towards the construction of an effective social policy for science. The first part of this book is therefore offered as a contribution to this problem.

The scientific and proto-scientific activities of man in prehistoric, classical, medieval and modern times are surveyed, in order to discover what social conditions are essential for the birth and growth of science.

It is concluded that the birth of modern science was completed in the seventeenth century. Since then, no fundamental innovation has been made in its method.

The rôles of freedom, class interest, national ambition, the repute of manual labour, and other social influences in the development of science are elucidated by attention to the history of science. But it should be understood that this book is not at all intended to be a history of science.

After the nature of science as a social product has been demonstrated, a few striking illustrations of the many events of the last three centuries which exhibit science in this light will suffice. The relations between navigation and Newtonian astronomy, Lavoisier's chemical theory and French social history, thermodynamics and the steam engine, and the general drive of a commercial civilization to discover the raw material of everything, which has culminated in modern electrical science, are among the illustrations chosen.

The reader then will wish to learn something of the conditions of science today. The scientist's personal motives, the nature of his scientific work, the conditions in which he works, the motives of those who set him to work, and many other influences to which he is subject are analyzed.

Thus the reader will finally gain some conception of how science has come into existence, the sort of social developments and conditions that have actually stimulated science in the past, and the social and personal motives which influence science today. He can then begin to consider what can be done, in the light of this knowledge, to create an effective social policy for science.

This book is offered as a possible selection of the data which will assist all interested in science to work out the best policy for it.

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J. G. CROWTHER

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INTRODUCTION

Some notes written in 1937, for lectures delivered in the United States on the social relations of science, make the best introduction to this book. They ran as follows:

"Thoughtful men and women have lost a great deal of pride in humanity during the last twenty-four years. The collapse of confidence in the soundness of modern civilization began on a large scale in Europe in 1914, with the start of the Great War. This vast movement of opinion did not have an equal effect in the United States, and still the American optimism is far greater than any which may be found in Western Europe. But American optimism is considerably less today than it was before 1929. A survey of the condition of the world does not suggest that confidence in the future will be easily restored. Since 1931 a series of obvious disasters has shown to even the most casual observer that the modern world is in a very bad way.

"No particular event in recent history marks the beginning of the present catastrophe. Each disaster seems to be a necessary result of what has gone before. If one suggests that the chief cause was the rise of Imperial Germany under the former Kaiser, one has to admit that the struggle of the Germans for a place in the sun, against the opposition of the English, who had grabbed a large part of the face of the earth, was not unreasonable. If one complains of the aggressiveness of British Imperialism in the nineteenth century, one may argue that it was the reasonable reply to the imperial ambitions of Napoleon. Historians also attribute the rise of German nationalism and imperialism to a defence against Napoleonic dictatorship.

"Besides nationalistic explanations of this sort, there are other, and perhaps deeper, causes of human dissension. Some

historians consider that the instability of the present human society is due to defects in its structure. They explain that the structure of society has been different at different periods of history. Everybody remembers that things were done differently in his own childhood. The differences were far greater one hundred years ago. Elderly people remember that different classes of persons used to wear clothes of quite different styles. A banker wore clothes of a fairly definite cut and texture. His clerk wore clothes of another style, and manual workers wore still other styles. You could see at a glance to which class any person belonged. Such guesses are very much more uncertain today. More than one glance at a lady's stockings is now necessary in order to determine her social status.

"These changes in the appearance and clothing of persons correspond to changes in the status of the work which these people perform, or of the class to which they belong.

"The enormously increased standards of dressing among the masses of the population reflect the greatly increased social power of the masses. When large sections of the population wear clothes of the same style as those of the bankers, industrialists, planters and politicians who rule the country, their psychology changes. Their mental attitudes become similar to those of their rulers, and then they begin to dispute whether they should not take the ruling into their own hands. If they are dressed as well as anybody else, they are as good as anybody else, and entitled to rule themselves.

"Thus the growth of the rayon or artificial-silk industry has had explosive social effects. By providing the masses with clothes similar, if not so exquisite, in style to those worn by the members of the governing classes, the rayon industry has contributed towards a profound change in the psychology of large sections of the population of the world.

"One may be sure that the tremendous development of the rayon industry in Japan has had a notable influence on the psychology of the Japanese people. Everyone in Japan is now

able to buy very cheap clothes of Western cut, and consequently look like Westerners. The sudden extension of Western fashions among the Japanese has powerfully stimulated their feeling of equality, and has perhaps overstimulated it into its present ferocious aggressions. One cannot believe that the Japanese would invade China as successfully if dressed in old kimonos as they are when dressed in the natty Western shirts and shorts they now affect.

"While it is impossible to fix on any moment as the definite beginning of the present terrestrial rot, the arbitrary date of 1931 is a convenient moment of reference. In that year Japan annexed Manchukuo, by the craven acquiescence of the English, and in spite of the admirable stand of Mr. Stimson. After Manchukuo came Abyssinia; Spain. We may expect that Czecho-Slovakia and Austria will be devoured by the wolves fairly soon.

"This is the state of the world in which we live.

"Now what is the chief characteristic of our age? The majority of persons would say that the chief characteristic of the present age is science; we are supposed to live in a scientific age.

"Then we ask, are undeclared wars and aggressions the natural blossoms of a scientific age? Are these the finest flowers of science?

"Scientists and others begin to meditate on what is happening, and then they ask whose is the responsibility. Are scientists responsible for what happens in a scientific age? Are they responsible for the results of science? If they are, what should they do about it?

"The degree in which modern life depends on science is rarely recognized. It is controlled by very ancient discoveries, besides very new ones. The enormous effect of radio, airplanes and machine-guns is easily seen. Radio is in some ways the most powerful instrument ever put into the hands of man. With it, one person may address instantly the whole world. It has been

of immense aid to governments and especially to dictators. The same idea may be put simultaneously into everybody's head. This produces uniform thought, which facilitates dictatorial discipline. The totalitarian states of today could not be ruled in times of peace without great difficulty if radio did not provide a denominator which uniformalizes the complications of a modern state. The influence of the radio in American politics is very well known. Its power in English politics was demonstrated very clearly in 1926, during the General Strike. On that occasion the radio was the sole source of information for the majority of people in England, and it delivered information only from the point of view of the government, which opposed the strike. At this moment, the Italians are stimulating unrest in the Mohammedan population of the British Empire by provocative broadcasts in Arabic. The Germans make similar provoking appeals to the German-speaking people in other countries.

"The radio, which has given so much aid to dictators, was developed into a practical form chiefly by Marconi. This Italian scientist and inventor joined the Italian Fascist Party at the early date of 1923.

"The other great invention which has had particular influence on the contemporary world is the gasoline engine. This has transformed the habits of a large part of the population, and is spreading the population through the countryside. But a far greater effect is exerted by the gasoline engine in virtue of the airplane. The development of the gasoline engine has made the airplane possible. This has been followed by the development of a new technique of warfare. Unarmed civilian populations may now be decimated and reduced to panic in a few hours. This has created a tremendous psychology of fear, on a scale that has never existed before.

"The triumphs of modern metallurgy have assisted the improvement of machine-guns. They are much lighter now, and will stand firing when red hot, without seizing. These improve-

ments allow the soldiers of modern armies to be equipped with machine-guns instead of rifles. This has enormously increased the firing power of first-class modern soldiers, and has given them an increased advantage over second- or third-class soldiers with old-fashioned rifles.

"But the improvement of technique does not always favour the aggressor, or those who at the moment control the military equipment. Radio assists dictators so much at the present time because, at the present stage of development of radio technique, large-scale equipment is required. As this is expensive it may be owned only by wealthy corporations or governments. Very few private persons could afford a transmitting station which could communicate with all the world. This is a temporary situation only. Further improvement of radio technique is making apparatus smaller and smaller, and more and more sensitive. In the future, every man will be able to make his own radio-transmitter, and carry it about with him in his coat pocket. Governments will not easily censor the messages transmitted by so many millions of individuals. So it is possible to hope that radio, which at present aids dictatorship, will presently work in favour of democracy.

"The development of the bombing airplane may also reduce its present aid to aggressors. Experience in Spain and China has shown that bombing of civilian populations does not always produce panic, but sometimes strengthens morale, if the struggle is not too uneven. All observers report that the civilian population of Madrid became far more anti-Franco after his air raids, and that it learned warlike resistance and discipline far more from Franco's bombs than from the exhortations of the Spanish Government.

"The great increase in the flying speed of airplanes has enormously increased the difficulty of hitting vulnerable objects on the ground. While great damage may be done by dropping bombs on big cities, because it is difficult to fail to hit something, the bombing of military trenches is becoming less effec-

tive. If the bombers are opposed by fast chasers, so that they cannot fly slowly and take deliberate aim, their chance of hitting zigzag trenches which have been properly constructed is small.

"Professional soldiers are not at all averse to a certain amount of bombing of their own civilian populations. Many English soldiers regretted in the war of 1914 that their bellicose relatives at home did not receive a large dose of bombing, for it would have taught them better what war is like.

"The increasing difficulty of aiming bombs caused by the tremendous speed of bombing machines has restored the confidence of naval authorities in the big battleship. Many countries are now building big battleships as quickly as possible. The naval authorities believe that the chances of hitting a battleship with a big bomb are becoming less. If the top of the battleship is covered with steel armour, the bombs must be dropped from a very great height, or they will not have enough momentum to penetrate the armour-plating. If the battleship is sufficiently big, it will carry a number of airplanes for chasing bombers. Thus the bomber which attacks a modern big battleship will have to travel very fast and very high, and it will rarely be able to hit its target.

"The increasing efficiency of the machine-gun is also tending in certain ways to reduce the effectiveness of modern warfare. The best machine-guns now fire so rapidly that they must be fed with vast and continuous supplies of ammunition. If all of the soldiers in an attacking, advancing army are supplied with machine-guns, vast and heavy quantities of cartridges have to be carried behind them. If they advance a few miles, millions of cartridges have to be carried, usually over rough country, up to the front line. The difficulties of carrying ammunition forward in sufficient quantities are becoming insuperable. The defending force has an enormous advantage because it can accumulate large stocks of ammunition; far more than the attack-

ing force can carry with it. Thus if the armies in a modern war are at all comparable in equipment and efficiency, the relative strength of the defending force is greater. The development of technique is making the ascendency of well armed over poorly armed forces far greater, but it is also steadily increasing the advantage of the defending over the attacking force. This is one of the reasons which explain why another world war is not very probable at the moment, whereas successful attacks by first-class powers on second- or third-class powers are increasingly probable.

"The discoveries and inventions of scientists affect modern life, and its social possibilities, at nearly every point. Without science, modern life could not continue for more than a few hours. This shows there is an organic connection between science and social life. The way in which science is involved in modern life shows that it is an intimate product of that life.

"The progress of science is commonly explained as being due to the curiosity of certain men named scientists. The scientist is supposed to be a man inspired by pure curiosity to discover new facts about the natural world. If this were completely correct, is it probable that scientists would always discover facts of practical value? Nearly all scientific discoveries have proved of practical value, and this value has generally been found more quickly than might have been expected. This phenomenon must have some meaning, for if scientific discoveries were due to pure curiosity there seems no reason why more than a few should happen to have practical value.

"The answer is that scientific discoveries are due not only to pure curiosity, but also to other factors, and that these other factors are usually far more important than pure curiosity.

"Science in the modern sense is only about three or four hundred years old. It arose about the same time as the Renaissance and the Reformation. No one would suggest that those great movements were due to science, but the apparition of the frag-

ile flower of science at that epoch seems to suggest that it was brought into existence by the same social forces which brought the Renaissance and the Reformation into existence."

Such were the views that one expressed at the end of 1937. What might be added to them in January, 1940, after writing this book?

Modern scientific communications, especially the radio and the airplane, have prodigiously contracted the size of the world as an administrative unit. A messenger may now travel from Europe to America in one-tenth of the time taken by an ancient Egyptian to travel from Thebes to Heliopolis. Messages and orders may be communicated to the population of the whole of the globe instantaneously.

These technical developments have enormously enhanced the strength of those in possession of power. Revolts have usually been started on the peripheries of countries. In Great Britain, for instance, many movements of opposition have grown in Devon and Cornwall, and in Wales and Scotland. Owing to their distance from London, they could become strong before the government's troops could arrive to suppress them. Troop and police operations may now be made almost instantaneously against discontented elements in the most distant regions, on orders from the capital. The general plan of operations for the whole country may be closely coordinated from the centre, and instant action taken to deal with unforeseen developments in places hitherto inaccessible.

The radio assists the possessors of power in one country to appeal to the populations of other countries. This is dissolving the effectiveness of geographical boundaries as bars to penetration by ideas. At the same time, the airplane is weakening the strength of natural fortifications provided by special topographical features of the earth's surface. The influence of such features on national history and character will decline, and it

may be foretold that where these have depended on such features, they will change.

England's insular situation has contributed much to her tradition of freedom. She has not been invaded for nearly one thousand years, and has depended on a navy rather than an army for protection. A navy is rarely quartered in a capital city, because its ships must be at sea. Its personnel is smaller and more highly skilled than that of an army. For all these reasons, it is less effective than an army for political oppression. While the degree of personal and political freedom in England should not be exaggerated, it is greater than in the majority of countries, and the long period of relative national security that she has enjoyed has been one of the conditions of its evolution.

The airplane has profoundly altered this condition, and it may be foretold that the English tradition and character will change as a consequence. The English are exposed to a new degree of danger, and they will tend to adopt more regimented habits in the new processes for self-protection. Through the new danger, they are exposed to a new fear, and this will make them more susceptible to the psychological suggestions of radio propaganda.

These objective circumstances show the need for positive action to strengthen freedom and democracy.

The tendency of society, on account of contemporary technical development, is towards unification and uniform organization. Government by a minority has rapidly grown easier, and it may soon be possible for a minority to govern the whole world as absolutely as a minority six thousand years ago governed the valley of the Nile. The ancient Egyptian dictatorship lasted about three thousand years. It was based on the minority's monopoly of engineering and administrative technique, which in the circumscribed conditions of the Nile valley gave its possessors exceptional power.

The stabilization of modern technique and its monopoly by

a minority might produce a world dictatorship comparable in completeness to, and perhaps as durable as, the ancient dictatorship in the Nile valley. It is improbable, but not inconceivable.

The example of Babylonia shows that technique is not necessarily static under such conditions. Invention and discovery probably progress most rapidly when freedom is spread through a population, but it may also advance, though less quickly, when it is restricted to a governing class that recruits to itself the ablest members of the population.

George Ellery Hale has placed at the head of the first paper in the first volume of the Bulletin of the National Research Council of the United States a quotation from De Tocqueville in which it is observed that the sudden fecundity of science associated with the French Revolution "is not to be attributed to democracy, but to the unexampled revolution which attended its growth." On this view, science is particularly stimulated by the social energy released in revolutions, but these may or may not be attended by a growth of democracy. Hale did not believe there was any necessary conflict between individual discovery and organized research. "A superficial view of the matter might suggest the conclusion that organized effort in science would hamper the individual investigator and hinder personal initiative. It is only necessary to examine cooperative research now in progress in astronomy, geology, and other fields in order to appreciate that the effect of well-planned cooperation is to stimulate the individual and to bring out his best and most original effort."

The analysis made in this book suggests that modern science has been associated with freedom because it arose out of the activities of the craftsman. If it had arisen from some other activity, it might not have been associated with freedom.

Modern freedom was invented by the early medieval merchants, who required it to justify the free use of capital, which was contrary to the principles of the medieval church. Their

more far-seeing leaders were in favour of a discreet extension of freedom for craftsmen, because this increased commercial profits when production depended on handicrafts. Freedom for a large number of persons is desirable when production depends on the efforts of a large number of individuals possessing their own small machines. It is not so clear whether it is necessary for a large number of persons when production depends on the efforts of a relatively small number of big plants or big machines.

The restriction on freedom in the present period is associated with the size and expense of contemporary machinery. For instance, only rich firms or states can afford to buy newspaper printing machines, big radio transmitting stations, synthetic rubber plants and modern armaments. Some modern processes cannot be operated by even the largest private firm at their maximum efficiency because they are too big and complex. The full possibilities of these processes could be realized only in operation by the state or, better, the world-state. When machinery has grown to this size it cannot be improved unless it is operated by the state, as any smaller scale will not present the optimum conditions for trial and discovery.

The forces acting against individual freedom are formidable, because they are due largely to the present stage of technical development. If radio, airplanes, and big machinery make dictatorship easy, there will be plenty of aspirants to use them for this purpose.

A degree of freedom and democracy evolved in the last three hundred years because it was necessary for the employment of capital and the development of production based on small machines. It was established as a tradition, but one of its chief supports has considerably declined. Freedom and democracy are now a tradition somewhat in conflict with the present stage of the evolution of technique.

The crises of modern society show that the freedom of property, which has the same status as that of life and liberty in the

Constitution of the United States—"No person shall be deprived of life, liberty, or property without due process of law"—must be restricted and perhaps eliminated if society is to be smoothly organized so as to avoid disintegration. Both the property and the machine bases of modern freedom are being sapped.

It seems that freedom exists only when it is advantageous to a stage of evolution of society. Hitherto, it was also associated with concrete things such as property and small machinery.

Is it possible that freedom cannot exist unless it is associated with concrete things? Is humanity unable to behave freely unless it has concrete counters to assist it, just as it is unable to manage its currency without concrete counters of gold, though these are not logically necessary? The only service of gold is as a check on the fallible human intellect. It is less difficult to fumble or deceive with a lump of durable metal than with a page of figures.

This would seem to confirm that freedom, which, like managed currency, is a sensible idea, also needs its material anchors. But private property in the means of production and small machinery are no longer so eligible for these tasks, as technical progress is tending more and more to demand state and world organization and large-scale machinery.

What will bring a return to increasing freedom? A method of establishing it by habit and law might be discovered in which all capital and big machinery is owned by the state, but the state itself is governed by a purely political organization. No concrete counters for freedom would be employed. Contemporary events show the difficulty of governing this sort of state without a powerful police. The allowance of private ownership in the means of production may be regarded as a bribe to distract predatory persons from direct interference with the government of the community. When it is eliminated, many of these persons will not work unless driven by police pressure, which leads to a great expansion of the police organization.

Then there is the danger that these persons may capture the police organization itself.

On the one side there is private ownership, spiritual vulgarity and some independence; on the other there is communal ownership, moral dignity and police supervision. The direction of evolution seems to be from the first to the second, as society based on private ownership of the means of production is, for technical reasons, working less and less well. One may therefore hope that mankind will quickly learn the conditioned reflexes necessary to live communally, so that the amount of police supervision may not increase indefinitely, and may soon decrease.

The success of such training is rather slender, as it does not attach freedom to concrete things such as private property and small machinery. A more substantial though not immediate hope is offered by the further development of science. At present science is developing in the direction of big instruments and organizations. It seems probable that it will evolve through this phase, and arrive at a new and higher one in which its instruments will again be small and compact. Science may show how a man can provide all his needs, in communication, food, transport, etc., from very small instruments and concentrated supplies carried in his pockets. Theory may show how the important features of the universe may be summarized in a few formulae, so that everyone may carry in his head the theoretical equipment for solving from first principles any ordinary problem arising in daily life. If science developed to this stage, it would provide new concrete bases for freedom.

More reflection on the meaning of the facts of history, and especially of the history of science and technology, is needed. Historians have tended during the last hundred years to devote themselves to fact rather than reflection. They were justified when they began this movement, because their predecessors' criteria of accuracy were poor and they rushed into speculation before they had secured sufficient facts. The reaction

against reflection and speculation has become excessive. Many professional historians are now permanently inhibited from drawing conclusions from their studies, and when they make the attempt their minds often falter, and they arrive at lame results. T. E. Hulme complained that the modern philosophers appeared as if they had been absorbed into a superhuman intellectual armour, until one saw "the armour running after a lady or eating tarts in the pantry," when it became clear "that it was not a godlike or mechanical force, but an ordinary human being extraordinarily armed." He noted that "it was in their *last* chapters" that "they express their conception of the world as it really is," and their conception often combined "exceeding commonplaceness" with "extreme subtlety" in argument.

Modern historical research has the same characteristics. The postponement of synthesis and the continual suspension of judgment have become a habit, whereas analysis and synthesis should proceed in parallel. Accidents are now needed to make great historians think, or at least compose their reflections. Would Pirenne have written his brilliant history of Europe if he had not been exiled in Eastern Germany in the last war? Would he have presented his argument so cogently unless he had been severed from all his books and notes, and forced to reflect for four years on the meaning of the knowledge acquired in his former studies?

The tendency to reject theorizing has become treason to civilization. If scholars refuse to think, their thinking will be done for them by diabolists. The success of Hitler is due in part to his provision of some kind of theory in the vacuum created by fact-hypnotized scholars. The social relations of science, like the rest, are in danger from him. He has been credited with the statement that "science is a social phenomenon, and like every other social phenomenon is limited by the benefit or injury it confers on the community. The slogan of objective science has been coined by the professorate simply

in order to escape from the very necessary supervision by the power of the State."

The scientists who have been contending that science has no social relations, is a purely individual activity outside politics, and arises solely from intellectual freedom are playing into Hitler's hands. Intellectual freedom is necessary for the advancement of science, but it cannot be guaranteed by appeals to the mere ideal of freedom. Resolutions affirming the necessity for freedom will not cut much ice unless the existence of material and secure foundations for it is explained and proved. Science depends on freedom, but it also depends on social relations, and at the present time the latter are the more important, as they are the less understood.

Hitler's view is extremely dangerous because in relation to the present situation it contains more truth than the conventional idealistic view. If scientists and other men do not clarify their understanding of the relations of science and society and acquire a firm grasp of the nature of the influence of society on science, besides the rôle of individual inquiry, they will find they have no protection against the important fraction of truth in Hitler's view, and they will be forced to submit to him, because he will prove triumphantly that he has the better understanding of science in the present social context.

The study of the history of science and technology seems to show that the prosperous periods in human history are due less to efflorescences of wisdom and more to new inventions which for a time reduced the difficulty of the material conditions of life. Humanity had a reserve of materials in these periods with which it could risk experiments. Progress depends largely on the creation of these material surpluses that make life less pressing and provide the conditions for experiment, and less than is thought on advances in the theory and organization of government, both of which are difficult and in each period present many problems beyond human power.

Partington has recently remarked, in his treatise on the

origin and development of applied chemistry, that "in the study of the development of man no part is more significant, even if more neglected, than that concerned with the use of materials." He was referring particularly to the period before 1500 B.C., but his comment is equally apposite to modern times.

The development of the United States could not have been achieved without the telegraph and innumerable other inventions. The demand for this development was the direct parent of many of them. Invention and science fertilized America. The expanding settlement in turn had a major influence in Europe. It provided an immense social safety valve. Capital and labour were exported, and the intelligent solution of their relationship in Europe was evaded and postponed. When America had become settled by the end of the nineteenth century, Europe was forced to solve its political, economic and national relations by rational arrangement, or suffer a series of social earthquakes. It drifted shiftily into the latter course.

The relative liberalism of the United States and Western Europe in the last hundred years has been associated with the fortunate possibility of evading social problems through the exploitation of the resources of a virgin continent by new inventions. It owes more to material superfluity produced by science, and the luck of finding undeveloped resources, than to innovations in political theory and morals.

Science has pursued a heroic career since the Renaissance. It has rushed forward in the glory of the potency of its new technique, and its success seemed to render reflection on the origin and nature of its method unnecessary. The seriousness of its effects on society have ended this period, and a new period of assessment and reflection has begun. This is represented by the new interest in the history and social relations of science. Knowledge of these subjects will soon become as necessary a qualification as arithmetic for a scientific career. The thousands of scientists and students of science in the

world cannot safely continue to ignore the relation of their own work to the rest of life.

Scientists' interest in the social relations of science is a self-analysis of science. The new study in one of its aspects is a sort of psychoanalysis of science. It soon leads from concentration on the internal logic to the relations of science, and reveals how much its rise and fall depends on forces in the social environment, external to itself. The next stage in the investigation shows that the central problem in the social relations of science, whose solution provides light on the possible future of science, is the nature and origin of the scientific method. Investigation seems to show that modern science germinated in the medieval period, and its development in the Renaissance was a continuation rather than an origination.

The fundamental factor was provided by the establishment of the repute of manual labour, which created the possibility of experimental science, which is the core of modern science.

The Greek scientists advanced rather like Don Quixote, with their ill-balanced combination of theory and practice, and they progressed towards knowledge slowly, in a series of magnificent beginnings and ignominious endings.

Graeco-Roman civilization was technically decadent. Its pessimism, which was absorbed by Augustine and incorporated by him into Christianity, was perhaps related to this. The Greeks failed to find a better basis than slavery for their society, so that their science, with the rest of their civilization, was like a hunchback with a beautiful face.

The history of the evolution of scientific method suggests that modern scientific method itself is not complete. The future may reveal factors which, when combined with present scientific method, will effect as great an advance in scientific method as did the combination of Greek theory with manual practice in the medieval period. The belief that modern scientific method is perfect is probably mistaken. This is encouraging, for a better method might lead to the solution of problems

at present quite beyond human powers. It is possible that the next advance towards this improved scientific method may be found through a combination of the present scientific method, which is generally conceived as independent of society, with social understanding.

London, January, 1940

THE SOCIAL RELATIONS OF SCIENCE

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I

WHY SCIENCE EXISTS

Science is the system of behaviour by which man acquires mastery of his environment. His evolution from an animal into a man was accompanied by a new attitude towards nature, in which he began to study the contents of his environment in order to use them to his advantage. His initiation of this activity brought science into existence, and at the same time began the transformation of himself from an animal into a man. It follows that science in the fundamental sense is virtually indestructible, and attempts to arrest its growth are contrary to a biological movement at least five hundred thousand years old.

Archaeologists divide the history of man into a series of ages, known as the Old Stone Age, the New Stone Age, the Bronze Age and the Iron Age. During each of these ages species of man used implements of characteristic types. The implements and the objects created with them, such as the foundations of dwellings, indicate the extent of the knowledge of nature possessed by their makers and the economy by which they obtained a living and multiplied. The size of the population in an age may be deduced from the number of burials that have survived. It has been found that the human population of the Old Stone Age, which lasted from about 500,000 until 25,000 years ago, was very sparse and its members belonged to species which have become extinct. These men could not stand erect. They had sharp teeth and powerful jaws more suitable than our own for fighting, and their brains were large compared with those of higher apes.

Men of an anatomical type almost indistinguishable from our own appear in graves belonging to the New Stone Age. It seems probable that the beginning of the New Stone Age is associated with the emergence of our own particular species of man. The number of burials surviving from this age is far greater than from the Old Stone Age, so it is concluded that the human population had greatly increased. The next relatively sudden increase in the number of surviving burials is associated with the beginning of the Bronze Age, and not with any notable change in the anatomical constitution of man. Since the Bronze Age, there have been only two major increases in human population, one associated with the invention of iron implements, and the other with the numerous scientific and technical inventions of our own period, of which steam and electrical power are particularly important.

It is not generally realized that the technical changes since the Renaissance are comparable only with those of the four past ages of man, and that we are living at the beginning of a fifth age as distinctive as its four predecessors.

The earliest human species were anatomically better equipped than we for fighting, but they were less well equipped than any other higher animal with natural armaments, such as powerful teeth and claws. They could overcome other animals possessing these natural advantages only by artificial inventions. They could use sharp-pointed poles and sharp broken stones as substitutes for teeth and claws. Their ability to make tools depended on the inheritance of binocular vision from animal ancestors. The two different pictures of any object seen by the eyes are combined into one picture through coordination by the eye muscles. The brain derives from these muscular movements an impression of solidity in the object, and a sense of distance. This faculty is restricted to man and higher apes. It provides the nervous mechanism for the delicate judgment of distance requisite for the control of the movements of the hand by the eye, upon which the development of manual

skill depends. Elliot Smith explained that this nervous mechanism and its controlling centres in the brain were in turn developed by the use of tools. This growth of the brain through the use of tools led to the anatomical changes by which species of animals became men. Experimenting with instruments is not only the activity by which man advances after he has evolved from the animal, but it is the cause of his biological change from an animal into a man.

Modern experimental science, which is the source of the contemporary advance in knowledge, has evolved from the prehuman experimentation with tools. There is no essential difference, though there has been a vast increase in subtlety, in the method by which man advanced five hundred thousand years ago and that by which he advances today. The invention of tools is the product of an attitude which is essentially scientific. It is therefore the first great achievement of science in the broadest sense, and it has had the social effect of transforming animals into men.

2

ELEMENTAL SCIENCE: TOOLS

The present geological era is about half a million years old and has been characterized by four ice ages. Pieces of flint which appear to have been intelligently chipped have been found in deposits laid before the first of these ice ages. These rough implements show that lower species of man existed more than half a million years ago. No remains related to the human species have been found with these roughly shaped stones, scarcely distinguishable from pebbles split by natural agencies, such as frost or fire.

The fossilized remains of a lower human species have been found in deposits laid shortly after the end of the second ice age, about 370,000 years ago. These remains, found in the cave of Chou-kou-tien, near Peking, are accompanied by very roughly shaped flakes of stone, and bones which have been burned. This discovery proves that lower species of man could make stone tools and control fire more than a quarter of a million years ago.

The manufacture of the simplest flint implement involves considerable natural knowledge. The maker must be able to recognize the best sort of stone and know where it may be found. This involves the first crude ideas of mineralogy and geology. The technique of making flint tools by striking one stone with another is difficult, and the early men who gradually developed it during hundreds of thousands of years must have learned through it much about the properties of stones, of their relative hardnesses and tendencies to cleavage. The impact of the stones would have given them crude ideas on elasticity and the inertia of moving bodies.

The first rough implements were probably for general use. Implements for particular uses, such as scraping or boring, were made much later, after a traditional technique of flint-working had been created, and could be applied to achieve a desired design.

3

FIRE

The traces of fire left by the Peking man show that the control of fire was known at a very early date. It may have arisen from early human experiments with eternal fires provided by escapes of natural gas and petroleum which had been ignited by lightning. Natural fires of this sort have been known for thousands of years in Iran. Early man would have less difficulty in acquiring knowledge of fire from a static source than from a dynamic natural forest fire or a volcano. It would have been difficult to approach such alarming phenomena with the calmness of experimentation, but all kinds of experiments could be made with a small constant flame issuing from the ground. In particular, the experimenter could ignite sticks in the flame, and then carry them to other places to provide new fires.

The discovery of the preservation of a natural fire by feeding it with wood was probably made long before the manufacture of artificial fire. The rites for the preservation of sacred fires, such as the Vestal fire at Rome, are a survival from the times before the discovery of artificial fire.

The control of fire is second only to the invention of implements in the history of the achievements of man. The most usual manifestation of natural fire is the forest fire, and this is even more terrifying than an earthquake. The other common form of fire is lightning, and this also is frightening. The early man who first approached these terrifying phenomena with the intent of control and exploitation achieved a marvellous triumph which involved psychological and practical elements

of equal importance. As Gordon Childe writes, he made a revolutionary departure from the behaviour of other animals, and was asserting his humanity, and making himself.

The psychological element of the triumph consisted of the courage found to approach fire objectively, and therefore without fear, and the boldness, no doubt at first unconscious, of the idea of exploiting not merely a great natural force but the most terrifying force in nature, whose reputation is preserved in the belief that fire is the most characteristic feature of hell.

Early man achieved a great extension of control over his environment through his mastery of fire. It provided him with artificial warmth, so that he could explore and survive in cold countries. The invention of cooking improved the variety of diet, and increased the available food supply by making inedible raw food edible. Part of the night could be turned to use by illumination from fire flames which removed the darkness. Caverns, which could be easily protected, made relatively comfortable homes when warmed and illumined by fire. He could unconsciously demonstrate his distinction from animals by frightening them away through their fear of fire, which they still had, but which he had subdued.

The properties of fire introduced him to a new world of change which is the basis of chemistry. It is said that the name of this science is derived from "quem," which is the hieroglyphic for Egypt, and also means black land or charcoal. Chemistry is associated from the beginning of history with a product of fire. Fire produces swift and impressive changes in matter. It boils water and reduces wood and flesh to charcoal and finally to ash. It splits stones and hardens clay. The observation of these changes extended early man's acquaintance with the properties of matter. The disappearance of matter in combustion showed that things can go out of existence almost instantaneously. This suggested that there is a principle of change behind the superficial phenomena of nature, and helped to sug-

gest that he might himself be able to disappear and reappear by an analogous principle.

The discovery of the artificial production of fire was probably made much later. The oldest method consists of drawing sparks from iron pyrites or haematite by striking them with flint, and using the sparks to ignite inflammable material. Modern savages also produce fire by friction between two pieces of wood, and by the heat generated in air compressed in a bamboo tube. Archaeologists consider that the variety of methods indicates that the artificial production of fire may have been discovered late in human history when man was already widely scattered in isolated groups.

The ability to produce fire and heat increased early man's sense of initiative beyond the degree necessary for the mere preservation of a natural fire. It gave him the power to produce at will a fascinating and potent thing very different from the normal environment. As Gordon Childe remarks, the evocation of flame from flint and pyrites looks very much like making something out of nothing. It must have exhilarated early man and increased his sense of creative power.

The social effects of the second great achievement of the essential scientific attitude, the control and production of fire, permeate all aspects of human life. Cooking, pottery and metallurgy are three of its offspring. The process of cooking trains observation and attention and develops taste, and had a great humanizing influence on early man. Fire increased the stability of his life, besides his mobility. He could build a more permanent and developed life with its aid in any convenient place. These conditions would be followed by an increase in the population, and in the complexity of the social relations between its members.

The overwhelming social importance of fire is symbolized in the legend of Prometheus. According to this, the gods owe their superiority to man to the possession of secret knowledge. Prometheus stole this secret for man, to enable him to rise to

a higher state. The myth is a recognition that the mastery of fire has transformed the status of man.

The early observations that heat may be produced by friction and by adiabatic compression of air are highly abstract, and different from common phenomena. The modern analysis of them has provided a large part of the evidence for the dynamical theory of heat and the laws of thermodynamics.

4

NATURAL HISTORY

Through nearly the whole period of his history man has obtained his food by gathering and hunting. It is assumed that early man lived on fruits, roots, shell-fish, eggs, and slain animals. The recognition of the sort and whereabouts of edible plants required the accumulation of considerable botanical knowledge. The successful hunting of large animals depended on exact observation of their behaviour and this would reveal its relation to seasonal conditions. The appearance of eggs in spring and fruits in autumn would also attract attention to the phenomena of the seasons. The assistance of moonlight in hunting and fishing would inspire exact observation and forecasts of the phases of the moon.

Early man's mode of living was impossible without a considerable knowledge of elemental mineralogy, geology, zoology, botany and astronomy. Archaeologists believe that he must also have begun to learn the technique of the organization of social units larger than the family, as the capture of big wild animals could not have been done successfully by a unit as small as a family.

It is to be expected that early man was interested in elemental medical science, and this is definitely proved. The Neanderthal men, who had a brutish aspect, could not hold their heads erect, and could not talk properly owing to chinless jaws, and could only shuffle along, flourished about fifty thousand years ago, before the onset of the last ice age. These men buried their dead in graves near the hearths in their caves. They protected them with stones from the pressure of the

earth, and provided them with stone pillows for their heads, and tools and joints of meat. These facts suggest that the Neanderthalers associated life with warmth, and believed that the application of warmth would restore life in the dead. The process of planned burial suggests that systematic treatment of disease was already in existence. If the dead were tended, then the sick were also tended.

The ritual burial proves that the Neanderthalers were capable of imaginative thought, for they could conceive a life after death. They were prompted to this imaginative effort, so remarkable in such physically brutish men, by their feeling of utter helplessness and terror at death.

"The pathetic and futile tendance of the dead" became a habit of man before he emerged in his modern shape. The belief in the survival of the dead, which is the basis of religion, is reflected in these burials, and is therefore very old. This evidence for the early existence of religion may seem of chief importance to many. Here, however, religious burial rites will be regarded as an illegitimate offspring of sound elemental medical science, and therefore a confirmation of its existence. The development of belief in survival was due to the lack of courage to face the failure of medical efforts to save life, and draw the correct conclusion from the absence of effects from burial near warmth. The lack of courage allowed the imagination to run beyond the facts and entangle itself in the false world of magic.

The existence of ritual burials implies some sort of traditional burial service. As the actions in the service do not lead to a material result, they become divorced from medical technique and material reality and grow into imaginative make-believe. This is a source of the arts of poetry, fiction and drama.

5

REFINED HUNTING TECHNIQUE PROVIDES LEISURE AND ART

The degree of culture rose to notable heights under the best conditions for gathering and hunting. Some men of the later Old Stone Age established camps at strategic positions on mountain passes used by thousands of migrating animals at the appropriate season. They have left immense middens of bones. In one of these, the remains of more than one thousand mammoths have been recognized. These large sources of food could support a considerable population who could employ their social organization and leisure for constructing buildings. Restriction to stone implements does not prevent complicated and permanent technical constructions, as the Red Indians of British Columbia built elaborate wooden houses in the nineteenth century while they were still restricted to stone implements.

The crude Neanderthalers died out about seventeen thousand years ago, some thousands of years after the end of the last ice age, and were replaced by men of species very similar to our own. The climate improved steadily with the retreat of the ice, and Western Europe became richly stocked with game. The new men exploited these conditions with success. They invented a variety of tools, and devised special tools for making tools. They invented the bow, which is the first mechanical engine. It operates by storing human energy during a slow contraction. When the bowstring is released, the energy is suddenly discharged and used to propel an arrow with great speed.

The increased stock of game gave scope for these improved weapons, and the combination of circumstances gave the new men an easier life and even some leisure. The human population increased far beyond that of earlier ages. As the mammoth disappeared in these times, its extinction may have been due to the improved hunting weapons, and to the larger numbers of hunters and superior zoological knowledge and organization in the chase.

These skilful and somewhat leisured hunters produced a realistic art. They have left some magnificent drawings and coloured paintings of animals on the walls of inaccessible caves. They reveal particular animals in active postures. It is thought that the artists believed that the lifelike representations gave magical assistance in the hunting of the animals for food. The accuracy of the drawings shows that the artists, who were also among the hunters, had progressed in zoological knowledge and recognized various species of fish and deer. They were also familiar with the physiological importance of the heart, as they have left a picture of a bison with its heart exposed and pierced by a dart. This no doubt represents a hunter's wish.

6

MAGIC

Advances in knowledge are always difficult. A slight improvement in technique may require the work of many men for a large part of their lives. When this has been achieved it benefits mankind forever, so the social profit on invention is naturally infinite. But to the individual inventors, the slight advance seems a trifling return for years of toil. Kelvin said on the occasion of the jubilee of his great professorship at Glasgow that the recollection of his career left him with a sense of failure. His achievements had fallen so far below need and desire. The same feeling probably afflicted inventors among early men with far greater force. The disparity between their inventive achievements and their desperate needs tempted them to relieve their sense of failure by self-deception. They added large spurious claims to the real advantages of any piece of technique to make it appear more potent and therefore more comforting.

The spurious accretion to a genuine process consisted of magical theories and operations. Magic was invented by early man to increase his sense of power and give him more confidence in solving the problem of living. He could not bear the plain facts of his helplessness, and he wanted something which gave quicker returns than technical invention. In his extremity, he convinced himself that magic could do this.

It was a product of his limitations, his difficulties, and the lack of a productive social system which could relieve them. It was invented by individualists, because it envisages the solution of the problems of life less by technical cooperation than by the enhancement of the personal power of individuals.

The population of early men was small, and their social

system was primitive. Under these conditions, they were individualistic, and looked for individualist solutions to their problems. The perception that the amelioration of man's condition does not come through the magical enhancement of the power of the individual, but through the accumulation of invention, occurs only after the evidence has been presented in the history of society over a long period.

The idea that man can best help himself by helping others is social, and arises after men have been organized in society for a long time. It is based on the observation that contribution of work and invention pays the individual, because in return for his single efforts he receives the benefits of the work and inventions of thousands of others. Isolated early man did not achieve this idea, because he lacked the social experience and historical perspective from which it could be drawn.

He was not in a position to recognize the effective alternative to magic. Thus magic, born of the contrast between the magnitude of early man's fear and the triviality of his technique, became strongly established in the most ancient tradition, and persisted, as it still persists, long after the rational alternative had become plain.

It declines, on the whole, as the cumulative achievements of technique become more manifest. But when at any period the difficulty of gaining and organizing life increases faster than the discovery of the appropriate technical solutions, as in our own time, the practice of magic temporarily increases.

As magic became established so early, all genuine technical processes, until recent times, were covered with growths of magic, like large cancers on small but healthy organs. There is no space here to describe the magical accompaniments of the operation of the wonderful technical inventions made by prehistoric man. No doubt they appeared to him bigger and far more important than the genuine operation, and their existence should always be kept in mind when the genuine elements in any prehistoric technique are being described.

7

EARLY APPLIED BIOLOGY

The accomplished hunters and gatherers of the last millennia of the Old Stone Age developed a discovery which brought that age to an end. Their ancestors for hundreds of thousands of years had included fruits and seeds in their diet. Some of these were wasted and scattered on the ground near caves where hunting families had lived for generations. They germinated and produced more seed, which was consumed as food. The cultivation of plants was probably used by the later hunters for augmenting the food supply for a long period before it began to approach hunting and gathering in importance. This occurred about eight thousand years ago.

The climate, which had been steadily ameliorating since the end of the last ice age, became notably milder and drier at that time, and more suitable for grass. The seeds of wild grasses, such as the ancestors of wheat and barley, became an increasingly important item of diet, and the auxiliary cultivation of them extended. Presently, in some communities, the cultivation of these grasses became more productive than hunting and gathering, and the communal economy was gradually adapted to cultivation of grasses rather than hunting. Though the change from gathering and hunting occurred recently and suddenly against the background of half a million years of human history, it probably took some thousands of years in absolute time.

The early agriculturalists who saved primitive wheats and barleys year after year must have had difficulty through the exhaustion of the fertility of the soil. They generally evaded

this by moving to new sites, as there was plenty of virgin soil.

The social effects of the development of agriculture were enormous and comparable only with those produced by the invention of implements and fire. Wheat and barley seeds are very nutritious, compact and lasting. They provide more food than almost any other means for equal amounts of labour, and they need little attention while growing. The growers of grain had more leisure than their predecessors, and much less difficulty in storing food for the winter. Their new technique allowed an indefinite increase in the population. Hitherto, the numbers of men had been limited by the amount of game and edible wild plants. These were relatively sparse. Increase in an agricultural population was unlimited as long as virgin soil was still available, for each extra member could support himself by acquiring a new plot of land. Agriculture greatly increased the scope of women and children, as many of its processes, such as weeding, unlike those of hunting, are not dangerous and do not require great strength. It seems reasonable to suppose that agriculture brought a big reduction in infanticide.

The surplus of plant food had another major effect. Food surpluses in the hunting age were irregular and consisted of meat. When they existed, they attracted dangerous animals. Plant surpluses attracted less harmful plant-eating animals. It is thought that the progressive desiccation of Northern Africa, due to the deflection of rain-bearing winds through the retreat of the northern ice, forced more and more animals to concentrate around the agricultural camps of men near lakes and rivers.

Numbers of animals came to depend on the agriculturalists for food, and grew tame, and presently were domesticated. The domestication of animals gave the agriculturalists a magnificent new store of fresh, mobile food.

As they developed their technique they were led to invent plant and animal breeding. The steady, almost unconscious se-

lection of the biggest grains of wheat for seed presently produced plants much more fertile than those of their ancestors. The extermination of unruly cattle provided docile herds. The milk production of herds was improved by selecting good milkers. Wild sheep are covered with hairs separated by only a little woolly down, and wool-covered sheep without hair were produced by selection.

The climatic changes since the end of the last ice age have shaped man's environment and his destiny. The melting of the ice was followed by millennia of tundra, and as the climate improved this was converted into steppe, and then covered with pine forests, and these were superseded by oak forests. The Old Stone Age extended into a period of wood. Flaked flint implements are unsuitable for cutting wood, so there was a motive for inventing tools more suitable for dealing with the forest, which spread like a gigantic weed and hampered hunting. The invention of agriculture occurred while the forests were still predominant, and may have had something to do with the worsening conditions for hunting. It also stimulated the demand for better wood-cutting implements in order to clear the forest for new fields.

New stone implements were invented under these circumstances, which give the name to the New Stone Age, or neolithic period. This age began about the same time as agriculture and therefore only about eight thousand years ago. It endured for a period very short compared with the half-million years of the Old Stone Age. The new stone implements were characterized by smooth surfaces and straight, sharp edges. Owing to these features they did not stick when driven into wood, but cut and cleaved through it. The smoothness was obtained by polishing, which is therefore typical. This process may have been suggested by the effect on stones used for grinding grain. It is suggested here, by the way, that the observation that warmth is produced in stones by grinding may have inspired the invention of fire-making by the friction of sticks.

The new smooth, straight tools stimulated the development of carpentry, and the improvement of building and furniture.

Pottery was another great invention of the new epoch. The meat captured by the Old Stone Age hunters could be excellently roasted or grilled without vessels, but the cereals of the New Stone Age agriculturalists required baking at a milder and steadier temperature. Ovens were improved for this purpose, and the discovery that moulded clay would harden and preserve its shape after being baked may well have been made in connection with them.

Pot-making provides the first example of the use of a chemical change for a constructive purpose, and it involves a series of difficult technical processes. Clay cannot be moulded satisfactorily unless it has the correct consistency. If it is too wet it disintegrates into mud, and if too dry it crumbles. If it contains no grit it will stick to the fingers in moulding, and if the bits are too large they will interfere with the moulding and weaken the material.

If the damp moulded clay is immediately fired, it will crack, so it must be dried first. Then it must be heated to 600° C. This produces the hardening, which is due to the expulsion of water chemically attached at lower temperatures to the aluminium silicate of which the clay is chiefly composed. The dried moulded vessel changes colour during the firing, and the resultant hue depends on the chemical constitution. If the clay contains iron oxide and is exposed to air while heated, the oxide will be oxidized further into red ferric oxide and produce a reddish hue. If the pot is heated in glowing charcoal, so that the air is excluded, the iron oxide in the clay will be reduced to the black ferroso-ferric oxide, which will make it grey.

The New Stone Age potter, who was probably a woman, learned all these phenomena, and how to manipulate them.

The painting of pots involves further successful forecasting of colour-effects produced by chemical changes through heat.

Paint which changes colour during heating must be prepared. This is applied to the unfired pot, and gives an artistic composition generally unlike that presented by the fired product. The patches of colour change, and the vessel shrinks. The potter must foresee all of these effects.

Owing to the existence of natural fuel which does not give a smoky flame, Asiatics solved these difficult technical problems earlier than Europeans.

The invention of pots had profound effects on human life. Cooking was transformed, and a variety of nourishing, economical and delicious new soups were invented. Jars could be used for preserving grain and oil, and for the preparation of fermented liquors. The observation of the changes which occur in mixtures of solids and liquids when heated in durable pots provided the data for an extensive development of elemental chemistry.

Again, the operations of pot-making provided a strong stimulus to the imagination. The moulding was a creative art, and the change from the dull damp moulded clay into the bright hard serviceable pot seemed not unlike a creation of life out of dust. The shape of the vessel was about the same before and after firing, but the material was quite different. This seemed to show that form persisted while matter changed.

The frequent use in the Bible and other ancient literature of the operations of pottery as similes for acts of creation shows the profound impression that their creative aspects made on the human mind.

The supplies of plant and animal fibres due to the inventions of agriculture and domestication provided the condition for the invention of the loom, another technical triumph of the New Stone Age. The simplest loom is a complex instrument, and weaving is a complex operation.

The new communities practicing agriculture, stock-raising, pottery, weaving and the associated techniques sprang up from the Nile to the Indus and beyond. The human population of

the world increased enormously. Though the New Stone Age did not last one hundredth of the period of the Old Stone Age, more than one hundred times as many skeletons have survived from it. The human population was therefore perhaps ten thousand times as dense. Even after this figure is pared down in various ways, the result still reflects the greatness of the new inventions. Yet the New Stone Age villages were small and none containing more than twenty graves has been found.

The women practiced pottery and weaving around a fire on the village green, before the huts. They chatted as they worked in common, and mothers trained their daughters in the techniques by apprenticeship.

The village was completely self-supporting, and though it was in communication with the next, there was little trade. There is no definite evidence that the inhabitants of different villages engaged in warfare. The weapons which have survived are not distinctively for warfare, and were probably used for hunting.

The implements left in any particular village are usually of very uniform design. As they were made and used by communal groups, it seems probable that this reflects a strong control of tradition over social habits. The products of the innumerable independent villages nevertheless showed wide differences.

It seems that young persons of initiative could easily leave an old village and found a new one where they could do things in their own way, and introduce changes which occurred to them. An innovation made in a new village striking enough even to impress the conservatives in the older villages could come into existence and spread.

The New Stone Age was a period of great technical invention, immense increase in population, peace, and a combination of conservatism with initiative. Its members concluded their effort in a blaze of technical achievement which provided the means for the final supersession of the ages of stone.

8

METALLURGY

As the few millennia of the New Stone Age passed, the climate in the Near East became drier, and large areas of fertile grassland became semiarid. The agricultural communities in these regions found life more difficult, in spite of improving technique, and their members were driven to give particular attention to favoured sites with steady supplies of water. The land adjacent to rivers, such as the Nile, which seasonally overflow their banks, was doubly valuable because it was well watered, and its fertility was renewed by the annual deposit of fresh silt. One crop could be continuously taken from the same plot, so the cultivators were encouraged to make their settlements permanent. This provided a favourable condition for large cooperative construction.

The original cultivable areas in the valleys of the Nile and the Euphrates were probably mounds surrounded by vast swamps. Though very fertile, they were small. The New Stone Age farmers who settled on them prospered, and gradually extended their size by draining from the surrounding swamp, until they had achieved the gigantic task of reclaiming the major parts of the valleys of these great rivers. In the valley of the Euphrates they created the land by covering the swamps with floating rafts of rushes, the method used by George Stephenson in laying the track across the Chat Moss swamp for his Manchester and Liverpool railway. The separation of the dry land from the water in the Biblical account of creation is a memory of the feat of the proto-Sumerians who raised the dry land of Mesopotamia out of the surrounding waters.

The accompaniment of all these technical achievements by magical practices has been mentioned in an earlier section. Unusual events and objects tend to acquire magical significance because their rarity suggests that they are mysterious and therefore have unknown powers. Objects which possess similarity of shape and colour are supposed to have magic connections with the things they resemble. Thus, coloured precious stones and rare minerals were regarded as magical. The colour of the brilliant green mineral malachite resembled the green of growing vegetation, so malachite became a magical symbol for fertility. The shape of cowrie shells resembles the female vulva, so they also are symbols for fertility. Farmers believed that they could guarantee the fertility of their land and animals and wives by decorating them with amulets made of these magical materials. Owing to the development of the technique of cultivation, the surplus production of cereals became considerable and part of it could be exchanged for these supposedly potent objects. The demand for precious stones and other magical objects led to the invention of trade after the prerequisite surpluses had been created through the advances in the technique of cultivation. Trade brings together in one place a variety of substances from different districts. The New Stone Age farmers lived on plains whose soil was fertile but poor in precious stones. These are usually found in rocky, mountainous districts. Their invention of trade brought coloured stones to them from distant mountains. They already had a considerable knowledge of the technique of the production of high temperatures through their invention of pottery, and had the means to apply intense heat to the new coloured stones.

It happens that many brightly coloured minerals are metalliferous ores. Malachite is a form of copper carbonate. If a piece were dropped into a charcoal fire fanned by a strong wind, the carbonate might be reduced to metallic copper by the hot charcoal, and shining globules of copper might run

out of the fire. This may well have happened many times in prehistoric Egypt, and when its significance was appreciated, the possibility of the science of metallurgy was discovered.

Pieces of native copper, gold and meteoric iron may have been known long before the invention of metallurgy. They would have been regarded merely as varieties of stone. The Red Indians of Lake Superior had many pieces of native copper from the local outcrops, but they failed to discover the possibilities of the metal.

Metallurgy was derived from the far more difficult discovery that metals may be obtained from certain stones by heating them with charcoal, or other materials. The phenomenon is in itself very remarkable, and must have seemed magical to the prehistoric men who first studied it. The complex change could not be appreciated without considerable knowledge of technical processes, probably acquired in making pottery. If this explanation of the discovery of metallurgy, which is advanced by authoritative archaeologists, is correct, the mode was typical of normal scientific discovery, where advance so often is made along a tortuous, highly technical path, though an obvious one is found after the discovery is made. The discovery of radio waves in 1887 is an example. This followed from the pursuit by Hertz of the highly technical path suggested by the theoretical researches of Clerk Maxwell. After Hertz's success, it became evident that Henry in 1842, and Hughes in 1872 had observed effects due to radio waves, but had not perceived their full significance. So prehistoric men saw stones of native metal, and even beat them into implements and no doubt saw some of them melt in fires, without discovering metallurgy.

Copper is tougher than stone and makes more durable tools, but its chief practical superiority is due to the possibility of casting it. From the perspective of a New Stone Age man, it is a reddish-brown stone that may be melted. A stone axe is soon blunted, and cannot be resharpened very often, because

each resharpening reduces its size. A blunted copper axe may be melted and recast with little loss of material, so it lasts far longer.

The invention of metal casting, like that of moulding clay for pottery, provided fresh scope for the creative imagination. The maker of a stone implement is bound by the piece of stone with which he starts. He proceeds by taking away bits of the stone. He does not add any material. He attains the desired design by negative, and not positive, action. When he moulds clay and casts metal he engages in positive creation, and consequently receives the higher psychological exaltation that comes from that sort of act. The invention of metallurgy stimulated the search for copper ore, which is not common and not easily found. This extended the knowledge of geology, geography and natural history, and led to the discovery of silver, gold and tin as materials for metallurgical processes. The development of the technique of casting involved great accessions of skill. The oxidation of the molten metal must be prevented, and air bubbles must not be allowed to form in the cast. The invention and preparation of moulds which will resist high temperatures is in itself a whole branch of technique. Copper melts at a temperature of 1200° C., which cannot be obtained without an air blast. Men stepping out of the New Stone Age must have found these technical difficulties very great, and their success in solving them is a measure of their achievement in science.

The lodes of copper ore on the surface of Near Eastern countries were no doubt quickly exhausted. Copper is generally found in combination with sulphur in the form of copper pyrites, but when copper sulphide is exposed to the air at the earth's surface it is gradually converted into copper oxide. Surface lodes usually consist of copper oxide, which may be reduced by heating with charcoal, as described. But when the surface lodes are exhausted, the ore-collector must follow the vein down into the earth. He then finds that the ore below is

sulphide. The extraction of copper from sulphide is more difficult than from oxide, and requires an additional process. The sulphide must be exposed to the atmosphere for weathering, so that the sulphur will gradually be removed by combination with the oxygen in the air.

Further, the ore-collector becomes a miner, and has to invent that technique which is a parent of so many advances in science. He must devise methods of boring hard rock, timbering of galleries, and preserving ventilation.

The bulky and heavy ores were rarely found near communities with a tradition of advanced technique, or in districts with copious supplies of fuel. They could not be utilized without improvements in the technique of transport.

9

POWER

Magic stones could be carried effectively on the person of a traveler, but ores and bulk surpluses of food could not. Transporting agencies more powerful than the human frame were required, and these were found in the harnessing of domesticated animals, and in the exploitation of the wind for driving boats. The efficiency of sledges was increased by the invention of the wheel, which was also made by prehistoric man. Wheeled vehicles are depicted in Sumerian art already in 3500 B.C. They were not used until 1650 B.C. in Egypt, when they were introduced by the Hyksos conquerors.

As the technique of cultivation improved, more and more labour was required for its operations. To meet this, the ox-drawn plough was invented. The productivity of cultivation was increased, and the mode was changed from the tending of small plots into the working of fields, which is agriculture, according to the word's exact meaning. The numerous technical advances in these communities of cultivators provided the means for the support of a great increase in population. The operations of farming had become complex, and could not be conducted efficiently without an accurate solar calendar. Accordingly, one was worked out, and was probably in use in 4236 B.C. in Egypt.

The inventions of land cultivation and agriculture, domestication of animals, the wheel, the sailing boat and metallurgy were all made in the period 6000–3000 B.C. They involve the recognition of major principles in biology, mechanics, dynamics, chemistry and physics. This spate of fundamental

achievement has not been approached in any other period, except the one which commenced about A.D. 1500, when science began to extend in a new way, and offers us visions as startling as those seen by the men of the New Stone Age when they first conceived agriculture and metallurgy, and the possibility of transferring their burdens onto animals and the forces of nature.

10

IRRIGATION

The good water supply and the sustained fertility of the soil made the valleys of the Euphrates, the Nile and the Indus exceptionally attractive after the technique of the cultivation of plants had been invented. Owing to the special conditions, the productivity of farming there outstripped that in the open countries. The surpluses were larger, and the trade for exploiting them was correspondingly more developed. The permanence of the fertility of the soil tended to make villages permanent. These circumstances favoured the growth of more complex technique, and this led to specialization. The extracting and working of metals cannot be done satisfactorily by any untrained member of a community. They require much knowledge and skill, acquired by specialization. The increasing surpluses of food provided the condition for the growth of specialization, as they could be used to feed specialists and free them from the time and labour they would otherwise have to spend on farming.

The necessity for reclaiming land from the original swamps in those river valleys gave an extra spur to cooperation and discipline in work. Unlike the migrating farmers in open country, the farmers in the valleys repeated the same operations in the same place year after year. They acquired a new degree of regularity in working habits, which assisted specialization. The tremendous feats of land reclamation by coöperative social labour gave the social will of the community great authority. This was symbolized by gods, who represented the ancestors who had in fact created the land. Permanent residence

was virtually a new social habit which strengthened affection for the site. Every feature had associations with parents and ancestors, and became a reminder of the idea of constructive achievement through social authority and organization.

The conduct of agriculture on land which is flooded seasonally demands the control of the flood waters. This entails the construction of drainage canals and banks, and the distribution of the flood water to the plots of every member of the community. The necessary engineering construction cannot be done by individuals, and the distribution of the water cannot be made without advances in the knowledge of hydraulics, and the development of a new degree of social foresight and organization.

The control of the distribution of flood waters created a new weapon of social discipline. If a farmer would not obey the rules of the society, or was obnoxious to the custodians of its traditions and therefore described by them as disrespectful to the gods, he could be instantly disciplined by the threat to cut off his water supply. Unlike an earlier farmer in the open plains, he could not leave the community if he was dissatisfied, and found a new farm elsewhere, because he could not undertake by himself the extensive engineering required in the reclamation of a new site from the swamp.

The achievement of new powers of construction and social organization involved some new limitations of freedom and initiative. The growth of specialization also increased the power of social authority, as it made more and more persons dependent on the community. A farmer could feed himself, but a smith had to be fed, so he wanted a strong social authority which would insist that he should not be allowed to starve, or receive an inadequate return for his products.

Specialization makes society far more complex, and this in itself leads to further development of the technique of social organization. It also leads to the concentration of production at a few sites, because specialist production is more efficient.

Stone Age farmers usually made their tools as they went along, from stones picked up in the fields. Every member of the community spent some of his time in making tools. But after the invention of copper founding, a few specialists could make enough copper hoes and axes for the whole community. The community therefore began to look to some group of specialists in a particular place for its supplies of tools. These tendencies, and others, were creating in the great river valleys of the Nile, the Euphrates and the Indus the conditions for the growth of a highly complex form of social organization in which social power was centralized, and numbers of dependent specialists were organized in dense communities at a few places.

This type of social organization is described as urban. The positive qualities of high and permanent fertility in the great river valleys were the fundamental conditions for its birth, and its growth was assisted by the excellent river transport, which facilitated the exchange of materials, or trade, necessary for a specialist system of production.

After this development had become established, the negative qualities of the valleys began to exert a stimulating effect. The lack of metallic ores and wood for fuel inspired pioneering expeditions to distant countries which returned with new knowledge of geography, geology, natural history, and inventions. The discovery of distant sources of raw material stimulated the improvement of transport, and ships and navigation.

In Mesopotamia even stones for implements had to be imported from distant Assyria by the Stone Age farmers, as there was no local supply.

II

ORIGINS OF ARITHMETIC AND GEOMETRY

The establishment of complex communities of specialists on permanent sites, or cities, was accomplished by the relatively sudden increase in population, unparalleled in earlier times except by that which occurred between the Old and the New Stone Ages.

The organization of life in the large and concentrated populations which could now be supported by a more efficient system of production presented numerous new problems. Storehouses of durable construction for keeping large surpluses of food were required. These were made of wood, and then of stone. The Mesopotamians had no stone, so they invented bricks. The city storehouses were essential to its life. For this reason, they were sacred, and were associated with the ancestral gods. It is not improbable that the utilitarian rôle of storage was more important than the celebration of religious rites in the first stone and brick buildings. The separation of the temple from the storehouse may have come later. The building of domestic houses out of stone and brick came later still.

The management of the central stores of grain, and the agriculture and trade by which they were accumulated, required a banking system, and was impossible without efficient means of keeping accounts and records of transactions. Owing to the superior importance of measuring food and money, arithmetic was invented before writing, so that mathematics is older than literature. The oldest known documents, both from Sumer and from Egypt, consist of numerals only.

The development of geometry probably received a strong stimulus in Sumeria through the invention of bricks, as many relations between lengths, areas and volumes are very simply illustrated by walls, cubes, and pyramids constructed of bricks of uniform size.

There is no good archaeological evidence for the theory that geometry was invented by Egyptians or Babylonians for surveying land, nor is there any evidence that the earlier Egyptians constructed right-angled triangles with strings three, four, and five units long, and thus knew a particular case of Pythagoras' theorem.

The growth of cities at different points along the banks of the same rivers, in lands which had already been completely settled, produced new elements of competition. The city populations used their food surpluses and technical skill for creating armies, in order to establish hegemony over their neighbours. Chief priests in city temples and other local leaders became generals and, as a result of their conquests, kings. Menes settled inter-communal disputes in Egypt in 3200 B.C. by conquering the whole country. Sargon conquered Mesopotamia in 2750 B.C. These kings began imperial expeditions for subduing the distant countries which provided raw materials after they had unified their own countries. The documents which rank next in age to the earliest numerical records of temple accounts are records of wars between neighbouring cities, and the treaties for ending them.

The expansion of the social unit from cities to countries and empires enormously increased the concentration of wealth, and the technical problems of management. The process of achieving it exerted steady pressure for the abbreviation of calculations and records. By 2000 B.C. the Babylonians had invented a numeral system in which the value of the symbol depends on its place, like that of the symbols in our own decimal system. They used a place-sign for zero about 500 B.C., but did not use it for calculation. With this mathematical

equipment, much of which was subsequently lost, they were able to make calculations with an ease unequalled thereafter until A.D. 1590.

The great development of Babylonian mathematics accompanied the conquest of the Sumerians by the Akkadians, who were a Semitic people. The Sumerians had created an elementary system of mathematics. The Akkadians swiftly developed its maximum possibilities, and afterwards Babylonian mathematics suffered a long but slow decline. According to Neugebauer, the phenomenon resembles the assimilation and extension of Greek and Indian mathematics by the Arabs. Knowledge of Babylonian mathematics reached India, and was probably the source of the growth of Indian mathematics. The Akkadian mathematics largely consists of abstract problems concerning lengths and areas. The subjects of problems were chosen only to illustrate methods of calculation, and the attitude shown in much of their work is philological.

It seems that very great advances in mathematics are connected with new contacts between cultures. A short period of rapid progress may then occur, while the possibilities of the new set of fundamental conceptions evolved from the contact is worked out. When the new mathematical tradition has been established, fundamental departures from it do not occur until it is supplanted in the next great change of civilization. If this theory is correct, fundamental advances in modern mathematics would appear to be impossible, because the population of the whole of the world is now in good contact. Perhaps the fundamental advances in the future will be due not to contact and assimilation between peoples with different cultures, but to assimilation between social classes with different cultures. Modern science, with its balance of theory and practice, would seem to owe much to contact between leisured scholars and manual technicians, and may be an expression of increasing assimilation of the two classes. It is possible that a fundamentally new mathematics will not be created until our own

civilization has died and the rediscovery of its ruins has provided inspiration to new peoples thousands of years hence, who will look at our mathematical knowledge with a new prospective, and see in it possibilities invisible to us owing to the particular cast given to our minds by the civilization we have inherited.

Writing was gradually evolved from pictures to systems of conventional signs. The Egyptians reduced their hieroglyphics to 500 symbols and the Sumerians their cuneiform script of wedge-shaped marks to 1,000. Even after two thousand years of development, writing remained difficult. A long apprenticeship was needed in order to learn it. This had profound social effects. The scribes became separated from the other specialist technicians. They were kept at the communal expense during their long studentship, and at the same time associated with their teachers, who were members of the executive staff of the palace and temple. While they and their profession required respectability through their associations, other technicians, whose skill may be learned more quickly, lost status.

In a document of about 1200 B.C. an Egyptian scribe gives this advice: "Put writing in your heart that you may protect yourself from hard labour of any kind and be a magistrate of high repute." The metal worker at his task at the mouth of the furnace has "fingers like a crocodile," and "stinks worse than fish-spawn." "The weaver in a workshop is worse off than a woman." He squats "with his knees to his belly and does not taste fresh air."

As the social status of trades and professions crystallized, they and the associated technical knowledge acquired certain degrees of respectability and vulgarity. Medicine was highly respectable because it was of urgent personal interest to the powerful. The causes of disease are obscure, and treatment had been associated with magic from very early times. Surgery was less respectable, because the poor were more liable to acci-

dents than the rich, and the causes of wounds are usually obvious. The scribes accepted medical knowledge as highly respectable, and therefore willingly wrote about it. They wrote less on surgery because they rated it lower.

The ancient Egyptian writings on medicine are numerous and bad, whereas those on surgery are fewer but include one outstanding work, which is probably a copy of an earlier work of 2500 B.C. This contains a classification of wounds which may occur to parts of the body, starting with the head and passing to the feet. Methods of examining the wounds, the conclusions to be drawn, and the treatments to be given are described objectively, and are evidently based on skilled observation and experience. The most remarkable feature is the plain statement that fourteen of the cases described in detail are incurable. This attitude towards illness is entirely alien to the magical, which would never admit lack of control over life and death.

Early surgical is superior to early medical science because it is a manual technique, which makes its facts so much more reliable. But that which gave it quality as science depressed its professional status, so scribes were loth to record new surgical knowledge, and thus hindered its improvement. There is no evidence that Egyptian surgery improved after 2500 B.C.

Surgery has sunk below the level of a respectable profession for long periods, and even today it is possible to hear that a man has been excluded from a club because he is a dentist.

The social stratification that accompanied urban development received a big impetus through the development of organized warfare. This was probably an urban invention, as there is no good evidence that serious warfare existed in the preceding New Stone Age. Successful war provided vast supplies of captives besides land and booty. It was more profitable to exploit than to kill them. They were turned into species of slaves. The harnessing of domesticated animals suggested that they also might be harnessed as sources of power. Though

not as strong as oxen, they could compete with them because they were more intelligent. Others were trained in the crafts of metal-working, weaving, pottery, etc.

The technicians of equalitarian farming communities, who had made the marvellous inventions of agriculture and metallurgy, the wheel and the sailing ship, bricks and the arch, wine and the solar calendar, presently found the status of their occupations depressed to that of slavery.

The techniques of numerical notation and writing were invented while the social traditions which provided the matrix of the superb creativeness of the millennia 6000–3000 B.C. were still alive, though declining with the rise of slavery.

The rate of invention slowed down, in spite of the increasing wealth, after slavery had become established as an essential and ancient part of the social system; say by 2600 B.C. From that date until 600 B.C., there were perhaps only four great inventions, the Babylonian place numerals in 2000 B.C., iron metallurgy in 1400 B.C., alphabetic writing in 1300 B.C., and aqueducts for city water supplies in 700 B.C. Only two of these were made within the immediate influence of the ancient cities, as iron metallurgy was introduced by the less advanced Hittites, and the alphabet was invented by Phoenician traders on the less-developed frontiers of the Babylonian and Egyptian empires.

The introduction of efficient iron metallurgy provided far cheaper and more durable tools. These brought within human power the possibility of clearing the dense forests, and solving the technical problems of life in temperate regions, which are more difficult than those in sub-tropical regions. The centres of civilization were gradually transferred through iron to the temperate regions of the earth, where they still remain.

The notable decline of invention after the stabilization of city life in Babylonia and Egypt occurs in parallel with the increase of slavery, the loss of status of craftsmen, and the con-

centration of wealth. The decline has been greatly obscured by the invention of writing, which was made about 3500 B.C., shortly before it began. Owing to writing, the details of the slow growth of knowledge during the period of decline are infinitely better known than the circumstances of the major inventions of farming and metallurgy in the previous creative age. The great bulk of the new written knowledge has produced a delusive impression of its qualitative importance.

Writing, including numerical notation and mathematics, was crippled as an instrument for the creation of knowledge soon after its invention, owing to its monopoly by scribes attached to the governing classes and despising manual technique. The scribes came to believe that manual knowledge, which is the basis of mechanics, biology, chemistry, physics and geology, was unworthy of the honour of record in the aristocratic technique of writing. This attitude continued beside a great use of mathematics in trade and architecture, and it had the effect, not of reducing the volume of mathematics used in these practical affairs, but of deflecting intellectual interest from the application of mathematics to subjects which were socially respectable. The subjects of highest respectability were religion and magic. They are imaginative, and consist of collocations of ideas which do not have any necessary relation with reality.

Writing is a technique. Its origin was practical, and it has marvellous qualities. But like all other technical inventions it has limitations. It is not particularly suitable for describing the phenomena of the natural world. It is impartial in its description of error and truth. Some day an inventor will devise a recording technique which will be automatically incapable of describing anything except the truth. Writing will not do this. In fact, in the short run, it spreads error more easily than truth, because it will record a free association of ideas which has little relation to reality. After these collocations of ideas are described in writing, they acquire a delusive reality from

the reality of the script. The phenomenon is the basis of the popular belief in the truth of the printed word.

The early writers acquired social prestige. Owing to this, anything in writing was important, and because important was assumed to be true. The scribes presently convinced themselves that writing was not a recording, but a creative process. The mere act of writing established the reality and truth of the meaning. Through this evolution, the scribes divorced writing and calculation, as techniques for assisting creative thought, from the manual techniques that are the most fertile source of new facts about reality, and applied them to the pseudo-facts of prophecy and astrology, from which knowledge could apparently be multiplied with flattering facility. Writing, like radio, was at first disappointing. It propagated and stabilized a great deal of error, besides much truth. It assisted conquerors to manage empires, as radio has so far done more to establish totalitarian dictators than to disseminate truth. With the other technical inventions it was seized and exploited by proprietory kings and priests who valued it as an aid to aggrandizement and prestige, rather than the conquest of nature for the benefit of humanity.

During the three thousand years of Mesopotamian and Egyptian supremacy from 3500 to 500 B.C. mathematics became more and more an aid to the accumulation of riches and the exploitation of astrology in the former country, and to the erection of pathological monuments in the latter. Its progress was disappointing, but through the long period the amount was considerable.

The earliest written documents of Mesopotamian origin, dating from 3500 B.C., contain addition and multiplication, and the area of a field is found by multiplying the length and breadth. Contemporary vases are decorated with chequer patterns which illustrate the rule.

Two systems of numerals were used in the fourth millen-

nium B.C. A decimal scale was used for measures of grain and beer, and a sexagesimal scale for numbering loaves.

During the third millennium the sexagesimal ousted the decimal scale, and place value, multiplication tables, tables of reciprocals and square and cube roots were introduced. In the second millennium B.C. simple quadratic and cubic equations were solved with these aids. Illustrative examples of the solution of particular problems in the calculation of the division of inheritances, rate of interest on loans, the dimensions of wells and storehouses, and the graduation of water clocks were compiled. This mathematical technique was not applied to astronomical problems until one thousand years after its use in trade, architecture and military science had begun.

Observational astronomy made more progress in Mesopotamia than in Egypt because of the retention of the lunar calendar, while the latter had adopted the solar calendar. The lunar calendar is more complicated, and is useless without incessant correction based on careful observation of eclipses and occultations. The Babylonians had observed in 2000 B.C. that Venus had returned to the same place on the horizon five times in eight years. Owing to their mastery of observation they were able to operate a time scale based on the division of the earth's rotation into twelve hours, whereas the Egyptians, with less interest in observation owing to their smaller interest in the moon, determined the watches by the length of light and darkness, which varies with the season. The Babylonian time scale, which is still in use, provides a uniform measure for the organization of affairs, and has greatly advanced the quantification of social life and thought, and so assisted the progress of science. The most brilliant astronomical results of Babylonian astronomy were obtained when the supremacy of Babylonia was ending.

A tablet of 650 B.C., which contains information which may be much older, describes an attempt to find a mathematical theory of the progress of the illumination of the moon's disc

while it is waxing. The disc is divided into 240 parts, and the spread of the illumination to the parts is recorded from observation. Attempts are then made to subsume the figures in an arithmetical and in a geometrical progression. The solutions are incorrect, but the exhibition of the method of research in mathematical astronomy, and the standard of mathematical technique employed in it, is profoundly important. The Babylonians attempted to discover a mathematical theory of a physical change involving movement by collecting observations and propounding hypotheses which might subsume them in a formula. There is no difference in principle between this method and that by which Newton discovered the law of gravitation. Nabu-rimanni in 500 B.C. gave the length of the mean lunar month correct to three places of decimals, and Kidinnu in 380 B.C. gave it correct to four places of decimals.

The Babylonians mastered the manipulation of equations, but as they always worked with positive integers and fractions, and as the roots of the majority of equations are not expressible in these numbers, they did not discover the idea of a general solution. Nevertheless, they constructed ideal problems which led to equations having positive and exact solutions. They could not have done this without having the idea that all equations might have a solution, and this was an advance towards the idea of the general solution and formal algebra. The construction of ideal problems is an exercise in abstract thought, and is a large step towards pure theorizing.

The Babylonians also advanced towards formal geometry, but did not discover it. They knew several cases of Pythagoras's theorem, and could deal with them through their knowledge of squares and square roots. They calculated the height of an arc of a circle in terms of the length of the chord and diameter, which involve similar triangles. But they did not discover generalized geometrical proofs. The limitations of their mathematical knowledge are thrown into sharp relief by their acceptance of π as equal to 3. This shows that their data

on the ratio of the circumference to the radius of a circle, derived from the direct measurement of circular objects, were very rough. The standard of accuracy is that of the ignorant slave rather than the instructed mathematician. It suggests that the direct measurement of circular objects, such as axles and cylinders, was delegated by mathematicians to craftsmen-slaves, to avoid the solecism of handling material objects. The slaves would not see the point of recognizing any tiresome difference from the convenient round number three, and the mathematicians would be inclined to believe that all relations created by God are expressible in perfect integers, rather than use their hands to discover the facts of the material world.

The Babylonian craftsmen who might naturally have learned a more correct value of π from their handling of circular objects were too debased to appreciate mathematical accuracy. The Egyptian mathematicians were far inferior to the Babylonian, but they found a more accurate value. Perhaps this was due to the higher esteem of art and crafts in Egypt. The lines of development of science and mathematics have been influenced from the earliest times by the relations between social classes.

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12

ORIGIN OF GREEK THEORETICAL SPECULATION

The urban civilization invented in Mesopotamia and other great river valleys diffused into the Stone Age farming communities in the outlying countries. Cities subsisting on trade and industry were established in Crete, on the Greek mainland, at Troy in Asia Minor, and other centres. Their inhabitants had adopted the bronze implements and the techniques invented in the original centres, and through lack of experience and discipline nevér reached the highest standard of skill achieved by the Babylonian and Egyptian technicians. The populations on the Mediterranean coast of Asia Minor were in a special position. Owing to their distance from Babylonia and Egypt, their social organization remained far closer to that of the Stone Age farmers, and therefore retained more of the peasant individualism which was associated with the supreme inventions of the New Stone Age. Their urban civilization was borrowed and, like most borrowed culture, was of the second grade, and for this reason was also less deep. The cultural traditions of Babylonia and Egypt lay on them less heavily, individualism survived, and yet there was a rough knowledge of what the ancient civilizations had accomplished. The Hittites, the Phoenicians and the Greeks, who were members of these populations, were able in these circumstances to make several inventions comparable with the greatest of the previous historical, if not the pre-historical, period. The Hittites invented the iron industry, the Phoenicians the alphabet, and the Greeks generalized thinking. All of these achievements

were made by people not overeducated in the urban tradition, independent, and still retaining personal initiative. It is difficult to say which of these three inventions was the most important, but there is no doubt that the Greek contribution is the most fascinating. Generalized thinking, like writing, charms and flatters the intellect, and is also ambivalent towards truth and error.

The individualism of the Greeks has been depicted in the *Iliad*. Individualism is regarded as a Greek invention by many distinguished scholars, but here it will be regarded as a survival from the tradition of the New Stone Age farmers. This internally free Greek society adopted organized warfare and slavery besides bronze implements from the Babylonians and Egyptians; like them they had two main social divisions: the governing class and slaves. But there was a very important difference. The Greek governing class was equalitarian among its own members by tradition, while that of Babylon and Egypt had grown authoritarian and theocratic. The attitude of both governing classes towards slavery was the same. Profound consequences followed from this situation. The Greeks had exactly the same attitude as the Babylonians and Egyptians towards the occupations of slaves. They regarded manual techniques as contemptible and beneath serious consideration. But they did not have the same attitude as the Babylonian and Egyptian governing class to the occupations of that class. They were unable to share their authoritarian and religious reverence for the results accumulated during thousands of years of activity in astrology, geometry, calculation, and other literary and theoretical sciences.

Homer's epics describe the struggle of the Greeks for power in Ionia. They are depicted as a young and technically backward people. Some three centuries after their victory, a group of Greek cities had arisen along the Ionian coast. They flourished in their security, and in their trade with Babylonia and Egypt. Their inhabitants heard a great deal of the technical

and other marvels of those countries, but as these were the product of a different governing-class tradition, they were unable to accept them without examination. Their detachment towards Babylonian ideas was also increased by nationalistic prejudice. Foreigners are usually more objective than natives in assessing the culture of any country.

The great Greek contribution to science was started by the Greek gentlemen in the rising Ionian cities, who began to study the hearsay which reached them of the literary and scientific activities of Babylonian and Egyptian priests.

The study of the technical activities of slaves was ignored from the beginning, so the Greeks were never able to develop an adequate science of chemistry, physics and mechanics. They did not even master the brilliant Babylonian numeral system, perhaps because the routine of enumeration had been simplified sufficiently by their time to be relegated to slaves, and had lost repute. Greek science bore the qualities and limitations set upon it through the social beliefs of its founders to the end of its thousand years' history.

The first great Greek contribution to science was made by Thales of Miletus, a city in Ionia. He had acquired great prestige through the prediction of an eclipse, doubtless made with the assistance of the Babylonian knowledge that eclipses occur at intervals of eighteen years and eleven days. He meditated on the Babylonian stories of creation, in which the universe was made out of water by God. This led him to the revolutionary suggestion that the universe consisted of water in a continual state of transformation, and he claimed the theory as his own. The absence of God as the creative agent and Thales' individualist claim of priority in the idea were original aspects in this theory. The theological scientists of the ancient countries could not conceive of cosmic action without God, and their priestly sense of duty and impersonality made them ascribe any new idea not to the person who discovered it but to God, or to the corporation of priests to which they belonged.

Thales included the stars besides the earth in his water theory of the universe. His ancient predecessors again would have found this inconceivable, as they believed the stars were gods, while he suggested they were steam from a pot. He proposed the theory that the universe consists of a self-developing process in one simple material. This remains today one of the leading ideas of science. He discovered it by separating theology from the ancient stories of creation, whose data were correctly though crudely drawn from observation of common phenomena.

His idea was refined by his fellow-townsman Anaximander, who proposed that the universe is unfolded in the evolution of a primary substance named the Indeterminate. This was eternal, infinite and endowed with a circular motion. As it persisted in time, the circular motion produced, or determined, features in it. Evidently Anaximander is the parent of the nebular hypothesis. Hot was separated from cold, and fire leapt upwards, forming the fires of the sun, moon and stars. The revoluuion of the stars was explained by a mechanism of fire and mist. Thales had believed that the earth rested on the primeval water. Anaximander advanced to the abstract idea that it is poised in space because of "the similar distance from everything." He deduced that the sea must formerly have covered more of the land because shells and marine fossils were found above sea-level. He suggested that animals evolved from drying mud and, after reaching the land, became adapted to life on it. "Man, in the beginning, resembled another animal, to wit, a fish."

He was influenced in making this deduction by the facts of embryology, for he noted that neither adult man nor his helpless offspring could live in mud in their present form, so their ancestors at an earlier epoch must have had intermediate forms.

A contribution towards the explanation of the mechanism of natural change was made by a third Milesian philosopher, Anaximenes. He suggested that the qualitative differences be-

tween the products of the stages in universal evolution were due to the rarefaction or condensation of the primary substance, which was mist. Fire was rarefied mist, water condensed mist, and earth condensed water.

The Milesian philosophers did not offer any proof that their theories were correct, or that the facts on which they were based were not delusions. They did not distinguish between the senses and the reason. Heraclitus, another Ionian, was the first to do this. He emphasized the fluxional aspect of nature, and contended that material facts are deceptive because matter is impermanent. He believed that appearances which endure for some time are due to a tension of opposites, or balance of forces in the universal flux, and that they could not be understood by the senses but only through the mind. "The eyes and ears are bad witnesses for men if the mind cannot interpret what they say." Heraclitus' criticism deflected attention more to the logical, and away from the observational aspect of theories. He had advanced towards the idea of the separation of mind from matter, though he had not reached the conception that the mind was immaterial. He believed that it was fire.

Heraclitus' theory of evolution through the tension of opposites was adopted by Hegel as the basic idea of his dialectic. Hegel deduced from it his theory of the absolute state, exemplified in German history.

The exaltation of the mental aspects of phenomena by Heraclitus in opposition to the theories of Thales and Anaximander is related to his social origin. He was a royal aristocrat, while they were merchants, or interested in trade. Anaximander made the first map, which was of the Greek trading posts in the Black Sea. Thales is credited with the application of geometry to the determination of the distance of ships at sea and the height of pyramids, and to have made a fortune by cornering the presses before a glut in olive oil. It was natural that Heraclitus, as a member of the governing class, was more

interested in ideas than in things, as the ruler is more concerned with aims than with the means for achieving them. Nor is it surprising that the aristocratic Hegelian theory of the state should have owed much to Heraclitus' thought.

Thales submitted the fragments of Egyptian and Babylonian mathematics which reached him to the same secular scrutiny that he had applied to the stories of creation. He had heard that a circle is divided into equal parts by any diameter. His predecessors used this fact without further reflection in the solution of problems. But he wondered why it was so, and is credited with conceiving and producing a deductive proof. He is credited with several other discoveries, including the proof that the angle subtended by a diameter of a circle at any point on the circumference is a right angle. These were the first known instances of general proof in mathematics. A general proof of any property of lines or numbers settles it in all cases, as long as the human mind works in its present mode. It eliminates forever the consideration of new particular cases, and is a prodigiously potent device for saving mental labour. Generalized thinking is apt to appeal to a governing class whose only labour is thought preliminary to command. In addition to its utility, it justly gives the human mind a sense of dignity and power over nature, though it is liable to produce an intellectual intoxication in which the mind forgets that its knowledge is derived from the material world, and is not spun out of itself.

The rise of generalized thinking among the Greeks is not inexplicable. It was due to various factors. One of them is the necessity for persuasion in an equalitarian community. The members of the Greek governing class were equalitarian for reasons which have been explained, and felt they had the right to reject hypotheses, especially those of foreign origin, unless they were supported by persuasive proof. The acceptance of assertions on authority was contrary to their social habits. Deductive proof is a systematization of the method of verbal argu-

ment by which one free man tries to change the opinion of another. It is less necessary in an ancient authoritarian community, where most of the particular problems of living in a certain type of society have been solved, and the solutions have been found through long experience. These solutions of many particular problems are collected, and taught by authoritarian rote, and the pupil is not accustomed to ask for proof, so there is no essential need for the development of a system of proof. It seems that generalized thinking has been invented to satisfy a practical need for a free group in society. The scientific achievements of the Babylonians show that their mental ability was unsurpassed. It is therefore reasonable to suppose that they had as much natural intellectual curiosity as any other people, but this did not help them to discover generalized thinking because that was not necessary for their social habits.

13

THE INCOMMENSURABILITY OF THEOLOGY AND SURDS

The Ionian Greeks did not know how to establish the truth of their bold naturalistic speculations because they had not discovered the method of collecting new facts in order to prove or disprove an hypothesis. They did not advance beyond the test, which they had invented, of logical coherence. Their brilliant intellectual attitude was modified, and was replaced by a partial recession to that of Babylonian theological science. The chief exponent of this new attitude was Pythagoras, who combined the Ionian discovery of general proof with the old Babylonian number mysticism. He and other Greeks were retreating from Ionia before the advance of the Persians, and fled to Italy, where they founded new centres of study. It is not unreasonable to suggest that they partially returned to Babylonian modes of thought because they were impressed by the superior power associated with Persia, the direct inheritor of Babylonian culture, and had seen how Ionia, together with its thought, had fallen before it.

On the positive side, Pythagoras and his colleagues greatly extended the application of Thales' idea of geometrical proof. They produced a logical series of geometrical propositions which were incorporated two and a half centuries later by Euclid in the first two books of his celebrated treatise. Pythagoras himself is credited with the brilliant theorem attached to his name, though his method of proof is unknown. The familiar proof is due to Euclid. The Pythagoreans produced a large volume of arithmetical researches which were partially

summarized by Euclid in his seventh, eighth and ninth books. They classified numbers in odd and even, and primary and secondary. They investigated the sums and properties of arithmetical series by studying tables of numbers arranged in various figures, such as squares and triangles. They discovered the theory of proportion, and arithmetic, geometric and harmonic means.

They were the first to teach that the earth is a sphere, and that it is not the centre of the universe. They attempted to explain eclipses by the hypothesis of an invisible counter-earth, which reminds the modern student of the explanation of the variability of some stars as due to eclipse by invisible companions. They discovered the arithmetical relation between the length of a stretched elastic string and the pitch of the musical note it emits when struck. This important deduction from the results of physical experiment was uncharacteristic, and all the more impressive, so they attempted to describe the revolutions of the celestial universe in terms of it. The earth and the stars were conceived as revolving around a central fire at distances proportional to intervals on the musical scale, and were supposed in the course of their revolutions to emit notes related to these intervals, which, however, were inaudible to human ears. The spiritual ancestors of these supernatural notes are, perhaps, Babylonian.

On the negative side, the Pythagoreans did not see these brilliant results in a modern perspective. They did not distinguish between reality and number and form. They identified reality with number and form. They believed that numbers, points and lines were concrete, and not abstractions from reality. In fact, they put the reality of numbers, points and lines first, and denied the existence of any phenomenon that could not be expressed in terms of them. In particular, they believed that number, and hence reality, was restricted to integers and fractions. These views could not easily have arisen except among thinkers belonging to a leisured class and

divorced from manual experience. They came into conflict with the generalized thinking adopted from the Ionians.

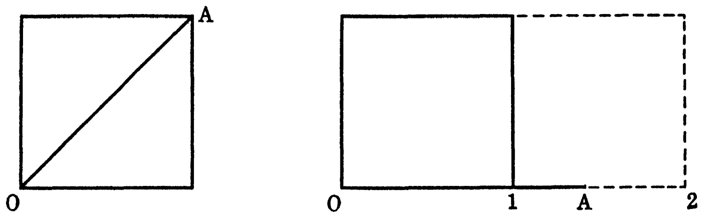
The Pythagoreans discovered that the square root of 2, which is the length of the diagonal of a square with sides of unit length, could not be expressed as a combination of integers and fractions. One proof is very simple. Suppose $\sqrt{2}$ is expressible as the vulgar fraction $\frac{m}{n}$ (which may be greater than 1). Suppose that it has been reduced to its simplest form, so that m and n cannot both be even. $(\frac{m}{n})^2$ must equal 2, so that $\frac{m^2}{n^2} = 2$, and $m^2 = 2n^2$. Hence m^2, and therefore m, must be even. Now, if m is even it must be divisible by 2, so it may be expressed as $m = 2p$. Hence $m^2 = 4p^2$. As $m^2 = 2n^2$, $2n^2 = 4p^2$, so that $n^2 = 2p^2$. Hence n also would be an even number. But as $\frac{m}{n}$ is reduced to its simplest form, m and n cannot both be even. Hence the assumption that $\sqrt{2}$ is expressible as a fraction leads to a logical contradiction, which proves that it is wrong. Hence $\sqrt{2}$ cannot be expressed as a fraction.

The Pythagoreans concluded that $\sqrt{2}$ is an irrational number, and all other roots, or surds, were irrational. This discovery strikes moderns as highly ingenious and interesting, but it affected the Pythagoreans quite differently. They believed that the universe was composed of integers and fractions, which were reality. They believed, therefore, that, as they had proved that irrational numbers exist, it is possible for reality to be irrational.

They were horrified by this conclusion, which they considered inimical to the reputation of the Creator, and attempted to keep it secret.

The impossibility of expressing $\sqrt{2}$ in terms of integers had further difficult implications. Suppose the diagonal of the unit square were laid along the line 02, which is the continuation of the side 01 to the distance of an additional unit. Its farther end would fall at A, between 1 and 2. Measurement would also show that A would fall between $\frac{4}{10}$ and $\frac{5}{10}$ of the distance between 1 and 2. It followed that $\sqrt{2}$ was slightly

greater than $1\frac{4}{10}$ and less than $1\frac{5}{10}$. More careful measurement would show that it lay between $1\frac{41}{100}$ and $1\frac{42}{100}$. This process could be continued beyond the limit of vision and measurement by squaring the numbers. This would show that it lay between $1\frac{414}{1000}$ and $1\frac{415}{1000}$. All of these numbers could be represented as points on the line 02. Now, the proof that $\sqrt{2}$ is inexpressible in fractions implies that though the approximation process were continued indefinitely, $\sqrt{2}$ could never be reached, and yet an indefinitely large number



of points corresponding to the approximation fractions could be marked on the line. Hence it follows that there are an infinite number of points on the line between those corresponding to $1\frac{4}{10}$ and $1\frac{5}{10}$, and indeed in any other finite interval, however short. Pythagoras had believed that the world was made of points, which had a small but finite size. The discovery that there was no limit to the smallness of points suggested that points were infinitely small, therefore did not exist. The basis of the world was an illusion, so the world itself must be an illusion.

Parmenides and Zeno of Elea in Sicily extended this type of logical argument. The flight of an arrow may be divided into a series of very small movements. During each moment, the movement is very small, and when it is infinitely small, the movement is zero, and the arrow is at rest. But the flight of the arrow is an infinite series of moments, during each of which the arrow is at rest. The arrow is therefore always at rest. They concluded that motion is an illusion, and that

reality is uncreated, indestructible and motionless. They identified it with God. The logical difficulties are due to the properties of infinite numbers, and have not been solved satisfactorily until recent times.

Their effects on Greek culture and technique were profound. The Pythagoreans had claimed as their chief glory that they had raised arithmetic above the needs of merchants. They boasted that they sought knowledge and not wealth, "a figure and a step forwards, not a figure to gain three oboli."

The line of criticism that they had started brought numbers themselves under suspicion as irrational, and their critical descendants banished from mathematics, with unconscious irony, that which the Pythagoreans had regarded as the stuff of the universe. The great mathematician Eudoxus devised a method of handling magnitudes which was independent of their infinite subdivisibility, and therefore of their expressibility in integers. This method, which is a forerunner of the modern calculus of Newton and Leibnitz, was perhaps the greatest Greek achievement in professional mathematics.

14

SOLVING THE CONTRADICTIONS

Numbers, and even diagrams, were subordinated by Eudoxus to a more refined mathematical logic. While they were being relegated to a secondary place in mathematics, they entered the life of society in a new way. Enthusiastic Pythagorean architects, such as Hippodamus, designed new cities on geometrical lines. Their influence was seen in the planning of the Piræus and many other cities, including at later dates Alexandria and Pompeii. Farrington remarks that New York, with its geometrical plan and numbered streets, is a typically Pythagorean city.

Sculptors tried to reduce the representation of the human form to an exercise in geometry and arithmetic. Mathematical aesthetics has revived at intervals ever since, not without notable effects. The infant Clerk Maxwell, in the middle of the nineteenth century, wrote his first paper, at the age of fourteen, on improved methods of drawing ovals of the type seen in Greek friezes, and his invention of the colour triangle, by which all colours may be made by a mixture of three primary colours, arose from his attempts to reduce the mixing of colours to mathematical rules. Maxwellian triangular diagrams are now used extensively for depicting the chemical and physical properties of substances containing varying proportions of three components, such as alloys and preparations in chemical manufacture.

Parmenides' proofs that the sensible world is an illusion could not satisfy many men, in spite of their excellent logic. Even the most leisured aristocrat could not feel quite con-

vinced by a conclusion so repugnant to common sense. Philosophers strove to find hypotheses which would admit the existence of change and be more consonant with common sense, but also would meet his criticisms.

Alcmaeon of Croton sought to prove the reality of sense knowledge by dissections of the body. He discovered the optic nerve, for he observed that the eye is connected to the brain by a nerve, and he correctly concluded that the brain is the seat of sensation. It seemed absurd to suppose that any connection between the eye and brain was necessary if visible objects were illusions.

Empedocles endeavoured to explain the multiplicity of phenomena by the hypothesis of four primary elements, which he took to be earth, air, fire and water. He suggested that material phenomena were a perpetual reaction between these elements, governed by mutual love and hate. He was groping towards the conception of elements governed by attraction and repulsion, but the idea of force had not yet crystallized.

He developed Anaximander's theory of biological evolution, and his views were paraphrased by Lucretius, who described how animals of strange types were born, but were unable to survive, as they could not gain food, reach adult age or mate owing to their defects.

Empedocles supported his materialism by at least one great experimental discovery. He filled a water-clock, which consists of a tube containing a small hole at the bottom end, and a lid with fine perforations, under water. When the clock was lifted out of the water upside down, so that the small hole was closed with a finger before the clock was lifted out of the water, the water inside the clock did not run through the perforations when the clock was lifted out. Empedocles concluded that air is tangible and exerts pressure. His proof that an invisible thing may have tangible properties strengthened his materialistic hypotheses.

His opposition to Parmenides' hypothesis of the changeless

indivisible reality was extended brilliantly by Leucippus and Democritus. The former came from Miletus and was therefore an Ionian, and the latter was a native of Abdera in Thrace. Leucippus agreed with Parmenides that there was a primary substance, but he disagreed with his assertion that empty space, or void, is unreal. He contended that reality consisted of pieces of the primary substance separated by void. The pieces, or atoms, were each eternal, indivisible, and changeless, but they formed all the continually changing phenomena of the material world by a flux of mutual combinations. This remains the most fundamental conception of the material world yet discovered, and is still the basis of theoretical science. With its aid, and starting from the postulates that "nothing is created out of nothing or destroyed into nothing" and "by necessity were foreordained all things that were and are and are to be," which assert the conservation of matter and the principle of determinism, Democritus gave a hypothetical description of the mechanism of nature whose truth was proved two thousand three hundred years later.

It is possible that Leucippus may have obtained inspiration for his ideas from India. The Indian philosopher Kanada, who may have been prior to him, but was probably not, supposed that matter consists of indestructible and eternal atoms which combine to form the five elements of earth, water, light, air and ether. Aristotle adopted a similar theory of the elements.

15

MEDICINE PRODUCES THE FIRST BALANCED SCIENCE

The hypotheses of evolution and the atomic theory were correct, but the Greeks failed to discover how to use them as guides to the collection of new observational and experimental facts which would decide their truth. This was owing to the general lack of contact between speculative thinkers and manual workers.

There was one profession in Greece, as in Egypt, which was partially exempt from this rule, for the reasons explained in an earlier chapter. This was medicine, and especially surgery. Greek medicine and surgery, like its predecessors, was descended in the main from the magical and sacerdotal practices of priests. This mixture of phantasy and fact was modified by two new influences: the hypotheses of the philosophers and the accumulated experience of the directors of gymnasia and military training. The first influence made medical theory more naturalistic, though not much more effective, owing to lack of combination with experiment. The second influence was more important. The directors of gymnasia acquired a traditional knowledge of the treatment of sprains and wounds, which had been accumulated by recording accidents, classifying them into various types, and describing the treatments and operations that had proved most effective for each type. This knowledge involved a combination of the results of long observation with skilled manual operation. It was a basis for conscious attempts to improve the technique of surgical operations, and this cannot be done without an element

of true scientific experimentation. Similar results followed from the development of treatment by diet and exercise. The patient was submitted to rational experiments in diet and massage.

A genuine experimental science was founded by these developments in medicine, especially in surgery, diet and gymnastics. It was distinguished by systematic observation, skilled manual operations, and rejection of magic. Its best achievements are exemplified by the writings attributed to Hippocrates of Cos. These contain the clinical observations of several diseases recorded through their duration for several weeks. The treatment is described, and the fatal end in the majority of cases is faithfully recorded. The observations are frequently masterly, and all are entirely free from superstition.

Epilepsy, known as the Sacred Disease, is described as "no more divine than any other. It has a natural cause, just as other diseases have. Men think it divine merely because they do not understand it."

The sense of scientific method had developed so far that the Hippocrateans not only rejected superstition, but attacked the speculative philosophers and "all those who attempt to speak or write about medicine with an hypothesis or postulate as the basis of their argument." They recommended philosophers to restrict their speculations to things in the sky, or under the earth, as these were not accessible to inspection and test. They claimed that medicine had accumulated a large quantity of reliable data, and had discovered a principle and a method by which many discoveries had been made over a long period. If the researcher started from those data, and used this principle and method, he would, if he was competent, make further discoveries, but if he professed to advance knowledge by any other means, he was a swindler.

The Hippocratean writings contain the first description of scientific method which contains all its elements. Their au-

thors had clearly understood that systematic observation, theory, and experimental test all had a part in the complete scientific method. Yet their instruction was soon forgotten and they were not the chief parents of modern science. How did this happen, in spite of the priority and brilliance of their work?

The Hippocrateans had the correct scientific method, but they could not advance science quickly because comprehensive scientific theories could not be derived from the material to which it was applied. The facts of human physiology are extremely complicated, and are among the most intractable subjects of research. The facts of medicine are unsuitable material for the foundation of science because they are not sufficiently simple.

The Hippocrateans' development of science was limited by the nature of the material presented to their study by their profession. The limitation was drawn by professional interest, and was social in nature. They were doctors first and scientists afterwards. Science did not develop quickly until its method was applied to the simpler phenomena of mechanics and physics, where it could soon deliver comprehensive results. It did not begin to do this until mechanics and physics became socially respectable subjects of experimental enquiry.

Medicine has given very much inspiration to the development of science, but it is not its chief parent. Many parts of it are still scientifically crude, and those parts which have become scientific owe their character more, on the whole, to advances in biology, chemistry and physics, inspired by other techniques.

Greek evolutionary and atomic theory failed because its proof depended on facts which could be learned only by systematic observation and experiment in regions of technique banned as socially disreputable. Greek medicine failed because comprehensive theories could not be derived from unsuitable

material. Not even the correct combination of observation, hypothesis and experiment is sufficient to guarantee the progress of science. The choice of suitable material for study by this method is equally important, and if this is prevented by social prejudice or limitation, science will not advance.

16

THE SOCIAL ROOTS OF PLATONIC PHILOSOPHY

The Greek conceptions of evolution, atoms and deductive proof remain one-half of the method of science. These great ideas were discovered by the inhabitants of the coastal cities of Ionia and Italy, before Athens had become the chief city in the Greek world. The dominance of Athens was due to the increase of her economic and military power, and was confirmed by her defeat of the Persians. Hoover remarks that "the silver mines of Mt. Laurian formed the economic mainstay of Athens for the three centuries during which the State had the ascendancy in Greece, and there can be no doubt that the dominance of Athens and its position as a sea-power were directly due to the revenues from the mines." Their prosperity was great before the Persian invasion. "In the year 484 B.C. the mines returned 100 talents to the treasury, and this, on the advice of Themistocles, was devoted to the construction of the fleet which conquered the Persians at Salamis (480 B.C.)." After the triumph of Athens, her leaders began to spend some of the spoils on the extension of culture. Philosophers from the Ionian and Italian towns were attracted by the new possibilities of earning a comfortable living by teaching. Anaxagoras of Acragas in Sicily, who was a philosopher in the Ionian tradition, came to Athens and converted Pericles from a belief in superstition. He asserted that the sun was a red-hot stone, and the moon an earthy body, and he gave the first correct explanation of the origin of the moon's light and the nature of eclipses.

Athens at this time was the richest and most powerful Greek city, but was culturally undeveloped. Her relation to the rest of the Greek-speaking world resembled that of New York to Western civilization in, say, 1900. Hart has described American civilization as lush. Athenian civilization had the same quality at this date. Athens produced no scientist of the first order in the whole of her history, and only two philosophers: Socrates and Plato. The scientists and other philosophers came from other cities, and settled in the metropolis, as Einstein, Fermi and Landsteiner have settled near New York.

Anaxagoras' progressive Ionian hypotheses grafted uneasily onto the less advanced ideas of the prosperous Athenians, who believed that the sun and moon were divine, and that Anaxagoras' naturalistic hypotheses of their constitution were sacrilegious. He was presently accused of atheism, and he had to flee, in spite of Pericles' influence.

Farrington has remarked that the painful adjustment to new ideas which occurred in Athens after the triumph over Persia is reflected in Aeschylus' works.

The Ionian philosophy was never accepted in Athens. Its limitations were becoming clear, and thinkers were beginning to perceive that it had no future. It consisted almost entirely of vast logical constructions based on a few observations, and truth became obscure in a maze of arguments. No one discovered that the Ionian hypotheses could be made fruitful by combining them with systematic experiment, as experiment was not reputable in a society supported by slavery.

The internal struggle for power in the Greek world, which succeeded the triumph over Persia, was reflected in the Peloponnesian War. This conflict excited the extremest corruption of politics and morals, and every weapon, including the sceptical Ionian logic, was used to discredit opponents. Sophists denied the existence of truth and goodness, and supplied plausible arguments to justify tyrants.

The Greek hypothetical science so far discovered was not in fact capable of solving current social problems, but the urgency of solution increased with the growth of Athenian imperialism. The disorder which affected Greek society was felt by many men, and of these the most gifted was Socrates. He believed that it could not be resolved without the reformation of the individual will. Society would not be good unless absolute goodness existed, and was recognized and adopted as a guide to conduct by its members.

Socrates did not succeed in deriving any help from Ionian physics and biology towards the solution of the problem of the individual will because these sciences appeared to be irrelevant, and their relativistic character seemed to throw doubt on the existence of any sort of absolute, including that of goodness. He concluded that Ionian science was inimical to the good life, and attacked it.

He believed that mathematics provided the evidence for the existence of absolute and divine truth. He adopted the Pythagorean view that reality consists of abstract ideas, such as mathematical triangles and circles, to which the features of the material world imperfectly approximate. The laws governing the relations between the perfect geometrical figures of reality are absolute truths. They are independent of experience, since, he contended, no one is convinced of geometrical truths by measurement of rough material objects. Mathematical truths are always and everywhere the same, and are therefore eternal. As the apprehension of absolute mathematical truth apparently did not depend on experience, Socrates concluded that it was due to a faculty of the soul inherited from a previous life, and was evidence for the immortality of the soul. As mathematical truths were the same for God as for man, they were divine, and illustrated the nature of God's mind.

Socrates was convinced that mathematics acquainted him with things which were absolute, divine and eternal. Confi-

dent that such things existed, he sought for the corresponding ideas of absolute, eternal and divine goodness as guides to conduct. He applied logic to the traditional conceptions of goodness in order to purge them of accretions from the material world, and reveal their perfect, eternal and divine form.

The governors of Athens at the time were persons who had secured democratic election through flattery of popular prejudices. They resented his criticism of traditional conceptions, and suspected that his views, like those of Anaxagoras, were subversive. They framed a case against him, and sentenced him to self-execution.

Socrates had addressed himself to wealthy and aristocratic young men in the hope that they would influence public affairs under the guidance of his opinions. One of these was Plato, who witnessed the final developments of Socrates' thought, and his end. Plato was profoundly shocked by what had occurred, and decided to devote his life and wealth to the propagation of Socrates' philosophy, and the training of a better type of statesman. He founded the Academy for this purpose, after some years of travel and study, when he was about forty years old. His institution lasted for nine hundred years. Plato used his unsurpassed ability to extend Socrates' conceptions of divine, absolute and eternal, mathematical, ethical and aesthetic truth, which existed independently of experience. He sought to base physics and astronomy on mathematics, and banish observation and experiment from science.

The subtle and beautiful new arguments in support of the Socratic principles fascinated the leisured Greeks, and soon made Plato the most famous philosopher in the Greek world. He was wealthy, and hated political democracy, as the death of Socrates had been decreed by democrats, and was a rigid adherent of the philosophical idealism he had so greatly extended.

When he was about sixty years of age he was called to

Syracuse to advise the young tyrant Dionysius II, who had just ascended the throne, on the reform of the government. He began by insisting on mathematical instruction for all members of the government. This procedure soon collapsed, and Plato returned to Athens in an atmosphere of amiable ridicule.

At about the same time, a change occurred in his philosophical principles. He admitted that experience was a factor in the acquisition of knowledge, and this led him to formulate the distinction between matter and mind, which is now an habitual conception of ordinary thought. But he did not relinquish his old Socratic position. He used his new insight to increase the subtlety of his supporting arguments. In his latest work he made a comprehensive attack on Ionian science. He denied that nature is prior to the mind, and contended that it is formulated by the mind through its interpretation of experience. He advocated worship of the gods, and the persecution of those who would not obey the principles of what he believed to be absolute goodness. He divided humanity into three classes, consisting of rulers, soldiers and workers, and advocated the inculcation of lies and superstition in the lower classes to preserve their subjection. He said that "any meddlesome interchange between the three classes would be most mischievous to the State, and could properly be described as the height of villainy." He sketched the constitution of the totalitarian state.

The philosophy of Socrates and Plato may be divided into major and minor parts. The major part consists of the rejection of naturalistic and experimental science, the assertion of the priority of mind over matter, and the support of religion and authority. The minor part consists of criticism of crude conceptions of the mind, religion and authority. This produced positive results of great importance, which entitle Socrates and Plato to their fame. They also encouraged the study of mathematics by their assertion that it was the basis

of mental training and acquaintance with reality. But the major part of their philosophy was retrogressive. The executioners of Socrates destroyed him because they were aware that his friends were aristocratic, and they suspected them of desiring to suppress the democratic development in Athens.

Platonism may be interpreted as a retrogression, though on a higher, subtler plane, to the authoritarianism and theocracy of the ancient empires. Ionian science was superseded by Platonism because its hypotheses were inadequately combined with observation and experiment, and it could not provide quickly enough the solution of the practical problems of organization created by the development of Greek society. It was easier to restore order by the imposition of imperialism from above than by solving the problems that lay at the foundation of the social structure.

17

A PARTIAL RETURN TO IONIAN REALISM

The greatest pupil of the Academy was Aristotle. He was the son of the chief physician to the King of Macedon. It has been explained in earlier sections that medicine was one of the few reputable manual occupations in antiquity. This was one of the conditions which enabled it in the Hippocratean school to acquire a true scientific method. Aristotle may have helped his father in operations, and have learned something of the Hippocratean method while he was still a boy. He was reared in an environment where certain sorts of manual operation and experiment were reputable. After this formative experience, he left Macedon at the age of seventeen and went to Athens to study in the Academy. He was overwhelmed by the brilliance of Plato's teaching, which was in the latest and most profound phase, and he remained under its spell until Plato's death about twenty years later.

As a good Platonist, his first studies dealt with mathematical and physical subjects, and he wrote treatises on astronomy and physics. The Platonic philosophy is seen at its worst in these subjects, and Aristotle's treatises reflected its defects. He asserted that the heavens are spherical, because they are perfect, and the sphere is the perfect form; and as their motion is eternal, and only circular motion is eternal, they must revolve in a circle.

He began his discussion of the properties of matter by asserting that earth and fire are contrary elements, one naturally moving downwards, and the other upwards. The existence of two more elements is deduced from earth and fire by Pythag-

orean arithmetical speculation. Earth is a solid and has three dimensions, and is therefore represented by the cube numbers 1 and 8. There are two arithmetic means between 1 and 8, that is 2 and 4, so these two Pythagorean realities indicate the existence of two more elements, evidently water and air.

These fantasies arose from his adoption of the Platonic belief in the prior reality of ideas. But he was incapable of entirely uncritical acceptance of speculations, and even in his early work began to modify his conception of the status of ideas. He asserted that geometrical forms inhere in material objects, and he distinguished clearly between form and matter. This distinction led him to formulate his theory of causation in terms of material, formal, efficient and final causes.

Aristotle presently conceived his four elements as materialized out of a primitive potential stuff by form. The elements are each distinguished by two primary qualities. Fire is distinguished by being hot and dry; air, hot and fluid; water, cold and fluid; and earth, cold and dry. He supposed that two elements might be transmuted into each other through their common quality. The alchemists presently justified their search for transmutation on his theory.

He explained the formation of metals and minerals by a theory of two exhalations, the vaporous and the smoky, which always exist together in greater or less proportion. The vaporous exhalation is produced by the sun's rays when they fall on water, and is cold and moist. When it is absorbed by the earth, it is compressed and dried and is the chief constituent of metals. The smoky exhalation is produced by the sun's rays when they fall on earth, and is hot and dry. It is the chief constituent of minerals. As the exhalations are never entirely pure, metals and minerals each contain the four elements, but metals consist chiefly of water and some air, while minerals consist chiefly of earth and some fire.

The phlogiston theory of chemical combination, which immediately preceded the modern theory of chemical combina-

tion, was gradually evolved during two thousand years from Aristotle's theory of the constitution of metals.

When Plato died, the direction of the Academy passed to his nephew, who was a mathematician. The Pythagorean tendencies of the teaching increased, and became unpalatable to Aristotle, whose thought was moving in the opposite direction. He left the Academy, and continued his critical revision of Platonic theories. As he had begun to restore the status of the reality of matter relative to form, he began the restoration of the status of sensation relative to reason. He concluded that reason is inseparable from sensation as form is inseparable from matter, and he became doubtful of the immortality of the soul. The inseparability of reason and sensation suggested that mental events might be affected by physiological conditions. If this was so, the truth of any idea could not be certain unless its freedom from physiological interference had first been ascertained. Truth was uncertain without preliminary physiological research into the behaviour of the thinking organism.

After about thirty years of study, Aristotle penetrated the Platonic maze, and concluded that systematic observation was necessary to the acquisition of knowledge. He founded the Lyceum, and devoted himself to biological research. Farrington has commented on the new elation of spirit which animates the style of his writing after he discovered a better path to knowledge. In his great biological works he describes five hundred species of animals; and he dissected fifty types himself. His classification of animals was not superseded until the eighteenth century. He recognized that whales are mammals. This was subsequently forgotten until the sixteenth century. He detected the heart in an embryo chicken in an egg four days after it had been laid. He noted a feature in the copulation of shell-fish which was not rediscovered until the nineteenth century.

His final submission of theory to observation is shown in

his discussion of the reproductive process in bees: "The facts have not yet been sufficiently grasped; if they ever are, then credit must be given to observation rather than to theories, and to theories only in so far as they are confirmed by the observed facts."

Aristotle, like Hippocrates, discovered the true scientific method through the study of biological material. He was the son of a doctor. Is it not probable that his devotion to scientific research in his later years owed much to the unconscious attitude learned in his childhood, and that a large part of the mental effort of his middle years was spent on escape from flattering Platonic fantasies?

His scientific triumph, like that of Hippocrates, was also incomplete. The Lyceum was soon closed, though the Academy persisted for nearly a thousand years. Platonism was more congenial than the later Aristotelian science to the Athenian society humbled by Alexander the Great. The study of science at Athens became fitful, and was illuminated only by brilliant gleams, like those of Heraclides, who was the first to suggest that Venus and Mercury revolve round the sun, and that the apparent revolution of the heavens is due to the rotation of the earth on its axis. The centre of the cultivation of science was transferred to the new capital at Alexandria.

18

IMPERIAL SCIENCE

Alexander the Great was one of Aristotle's pupils. He instructed two thousand officers throughout his empire, which extended from Spain to India and from Russia to Egypt, to collect scientific and political information of interest to his former tutor.

Aristotle could not have accomplished his remarkable work on the classification of animals without being supplied with data by an imperial service. Conversely, an empire cannot be managed without exact knowledge of its extent, topography and contents. The accumulation of knowledge was of practical value to the new administration.

Alexander had learned respect for culture from Aristotle, and he knew from experience the practical value of knowledge. His best officers acquired the same view. After his death the empire was divided among his generals, and one of these, Ptolemy, became king of the Egyptian part, and established his government at Alexandria, where he energetically cultivated the tradition. He called Strato, the contemporary director of the Lyceum, and other scholars to his capital to establish scientific research. The Lyceum was closed after the loss of its director, and its unique philosophical library was transferred to Alexandria. A system of organized scientific research was created around these nuclei of men and equipment, through the enthusiastic encouragement of the Ptolemies. They established the Museum, which was a development of the personal schools of Plato and Aristotle into a university, where many specialists could study the numerous new sub-

jects which were branching from the comprehensive studies of the earlier masters.

The Museum had its superb library, lecture halls, dissecting rooms, zoo, botanical garden and astronomical observatory. Its staff consisted of about one hundred professors, and included most of the best scientists in the world, owing to the attraction of the unique equipment and high salaries. It was opened about 300 B.C., and one of its earliest professors was Euclid, who joined the staff when he was about thirty years old. He died after teaching in Alexandria for about twenty-five years. His treatise on the elements of mathematics, which remained a standard textbook for two thousand two hundred years, and became the most famous ever written, consists of a systematization of the geometry and arithmetic taught in the Academy, but freed from philosophic fantasies. Though a large part of the results given in the text was discovered by his predecessors, he devised the thoroughly logical order. He invented the familiar form of enunciation, statement, construction, proof, and conclusion. As he wished to develop the proofs in an evolutionary order in which each new proposition could be deduced without additional assumptions from those which were already proved, he had to exclude many ancient proofs which would not fit into the order, and discover new ones.

Euclid's geometry is derived from the properties of real objects and is based on mensuration. The degree of its dependence on the concrete objects of the world of common experience was not realized until the development of projective geometry in the last century. Euclidean geometry is a very special case of a more general geometry. He was a profound mathematical investigator, besides being a great logical systematist. He discovered the twenty-five different incommensurable magnitudes which may be expressed as the square root of the sum or difference of the square roots of two commensurable magnitudes. No advance on this study of incom-

mensurable magnitudes was made for one thousand five hundred years.

He followed the Platonic rule of using only those constructions which could be made with a ruler and compasses. He wrote several other works, including one on conic sections, and another on physics. This dealt with optics, which was needed in connection with the stage. It is significant that it starts with a mistake, for he asserted that objects must be seen by rays emitted from the eye in straight lines, "for if light proceeded from the object we should not, as we often do, fail to perceive a needle on the floor."

Aristarchus of Samos was twenty years younger than Euclid. He came to Alexandria, and was the first to propose that the sun was the centre of the universe, and that the earth revolved around the sun. He calculated the distances of the sun and moon, and the ratios of their radii to that of the earth by correct methods.

Archimedes was forty-three years younger than Euclid, and graduated in Alexandria. His predecessor's textbook had already become a classic, for he quoted it by book and proposition in the course of his own proofs. Archimedes returned to his native Syracuse after his studies, as he was a member of the royal family, but as a mathematician he retained contact with Alexandria.

Archimedes used only two principles in addition to those employed by Euclid. He assumed that of the lines joining two points, the straight line is the shortest, and of two curved lines which join the two points, that which is nearer to the straight line is the shorter. He knew no trigonometry or algebraical geometry, but he derived a process close to the integral calculus from the method of exhaustion. He deduced the area and volume of the sphere, and the area of the parabola, the ellipse, and the spiral curve which bears his name, with this limited equipment. Mathematicians agree that this exhibition of skill has never been surpassed. He also wrote works

on mechanics and hydrostatics which contain the only two important general results obtained by mathematical physics in antiquity. He stated the exact theory of the lever, that "magnitudes whose weights are commensurable will balance if they are hung at distances which are inversely proportional to their weights." He deduced this formula from the axioms that equal weights placed at equal distances from the point of support balance, and equal weights placed at unequal distances do not balance, but that which hangs at the greater distance descends. No improvement on his proof was made until A.D. 1586, and a fallacy in his argument, by which he assumed that a number of weights spaced out along one arm of a lever will have the same turning effect about the support as if they were all collected at their centre of gravity, has been noticed only recently. As Cox has remarked, Archimedes seemed to have deduced a physical truth from axioms assumed as self-evident apart from experience, though careful scrutiny shows that he did not succeed. But his theory of the lever was of immense practical value, for it enabled engineers to calculate the dimensions of levers for any particular task. This saved time, and prevented accidents due to attempts to move excessive weights by weak levers.

Archimedes deduced the centres of gravity of many figures, including parabolic areas. He probably found them by experiments with parabolic shapes cut from sheets of thin material, and then proved that the point must be the centre of gravity by geometry.

His interest in hydrostatics was aroused by an effort to determine whether the gold in the crown of his relative, the king of Syracuse, was pure. The goldsmith had been provided with a certain weight of gold, and the crown was of the same weight, but it was suspected that some of the gold had been removed, and replaced with an equal weight of silver.

Archimedes observed while in a bath that the pressure on his body increased as its submergence progressed, so its ap-

parent weight in water must be related to its volume. He obtained pieces of gold and silver of equal weight in air, and weighed them in water, and found that the apparent weight of the silver was now less than that of the gold. It was evident that the purity of the crown could be tested at once by comparing its weight in water with that of a piece of pure gold which had the same weight in air. According to tradition, the experiment proved that the goldsmith had defrauded the king. The discovery of Archimedes' Principle was inspired by a commercial transaction.

Archimedes proved that the surface of a fluid at rest is part of a sphere whose centre is at the centre of the earth. He deduced that the pressure on a floating body is equal to the fluid displaced, and he solved problems such as the limit of density of a paraboloid which will float in water in equilibrium.

Archimedes gave great aid to his city when it was attacked by the Romans. His catapults and other contrivances prevented direct assault, and the city was captured only after a long siege. He was killed contrary to orders in the sack of the city after it had been captured. His patriotism was reflected in his prose, for he persistently used the Doric dialect. But his style was elegant and powerful, and gave a perfect expression of his ability. His fame as an inventor was immense, but he left no accounts of his devices, as he believed that researches that aided manual labour were disreputable.

The third great mathematician of the early Alexandrian period was Apollonius. His ability was systematic, like Euclid's, and he succeeded in giving an exhaustive account of the geometry of conic sections, the curves formed by slicing a cone in various directions. Little practical use was made of his researches for two thousand years, until Kepler employed his geometry of the ellipse in the account of planetary motions.

The greatest geographer of antiquity was Eratosthenes,

who was twelve years junior to Archimedes, and one of his personal friends. He was librarian to the university at Alexandria, and was also distinguished in astronomy, athletics, and literary composition. He proposed the Julian calendar containing one extra day every four years, and he measured the diameter of the earth, and may have obtained a result correct within fifty miles. He had observed at Syene on midsummer noon that the sun was directly overhead, as it was visible from the bottom of a deep well. At the same moment, when the sun was observed from Alexandria, its angle from the vertical was one-fiftieth of the circumference of the circle. The radius of the earth is easily calculated from the distance between Syene and Alexandria, and this angle.

Eratosthenes used his skill in astronomy for improving the accuracy of maps. He incorporated existing geographical knowledge in a map of the world as known to him, which consisted of the countries between Gibraltar and the Ganges. He divided the map with reference lines which are forerunners of lines of latitude and longtitude.

The work of Eratosthenes was of great practical value to the maritime empire of the Alexandrians. Geography was a reputable form of knowledge, as it was personally necessary for the directors of military and economic operations. Like the measurement of time, it provided a means through which practical affairs and pure astronomy could fertilize each other.

The greatest astronomer of Greek antiquity was Hipparchus, who studied at Alexandria about a century after the time of Eratosthenes, and then settled in the island of Rhodes. He was a very accurate observer, and discovered the precision of the equinoxes (due to the swaying of the earth's axis, like that of a top). It has the effect of altering the apparent position of the fixed stars by fifty seconds of a degree each year. Hipparchus estimated the effect at fifty-nine seconds a year. He gave the lunar parallax, the angle subtended by the earth's radius at the centre of the moon, as fifty-seven seconds, which

is virtually correct. He measured the eccentricity of the sun's apparent orbit, which is the degree of its deviation from a perfect circle, and obtained a figure correct within about five per cent. He determined the duration of the year within six minutes. He made several other fundamental astronomical measurements. In addition, he invented or established the epicyclic theory to account for the observed irregularities of planetary motions. This accurately described all astronomical observations then known, and improved the accuracy of the forecasts of eclipses. He was inspired by the appearance of a new star to compile a catalogue of the positions of 1,080 fixed stars. This catalogue was lost, but his scheme was repeated by Ptolemy in A.D. 137. Tycho Brahe did not catalogue more than 1,005 stars in A.D. 1580, as, like Hipparchus, he was still limited to the naked eye.

He virtually invented trigonometry and was the first to denote the position of places on the earth by their latitude and longitude. No fundamental improvement on his theoretical astronomy was made until the time of Copernicus, and little on his observations until the invention of the telescope. His achievement was based on a good knowledge of Babylonian astronomy, combined with the mathematical theory which had been elaborated in Alexandria, and his own ability.

Notable advances in biology were made during the first fifty years' study at Alexandria. Herophilus systematized anatomy, and compared the structures of dissected human and animal bodies. He was the first to distinguish clearly between arteries and veins, and he recognized the brain as the centre of the nervous system and the seat of the intelligence. He gave certain parts of the brain the names they still bear. His contemporary Erasistratus also studied the brain, and distinguished between the main brain, or cerebrum, and the lesser brain, or cerebellum. He associated the complexity of the convolutions of the brain with the degree of intelligence, and he distinguished between motor and sensory nerves.

19

THE DECLINE OF SCIENCE AT ALEXANDRIA

The advances in sciences described in the last section occurred within one hundred and seventy-five years from the establishment of the Alexandrian science schools in 300 B.C. They were accompanied by comparable advances in other branches of culture, as grammar was evolved by the study of the accumulated materials in the libraries, and the observation of the increasing difference between contemporary language and that of the older manuscripts assisted the development of philology.

The early Alexandrians made great contributions to knowledge, but their greatest achievement was systematization. They created the educational system, and made knowledge easily communicable, so that it could be converted into an instrument available to a much larger part of the population. Archimedes was the most brilliant Alexandrian. He was a physicist by nature, one who applies mathematics to the interpretation of the properties of matter, but he was unable to develop his chief gift fully, owing to the prejudice against manual experiment which he had acquired from his social environment. Euclid was a less brilliant, but greater figure. His method of teaching geometry still has a fundamental part in mathematical education, and in so far as it remains in use, it is one of the chief means by which geometrical knowledge is communicated, and placed at the service of man. It is therefore of great practical value.

Modern teachers of mathematics are, however, no longer under the spell of Euclid. They recognize that his method is still the best for teaching mathematical logic and proof, but

that it does not develop skill in solving practical problems by geometry. Other and equally important methods of teaching geometry are required for this purpose. Matter is not precise, like the abstractions of geometry, and the elucidation and utilization of its properties in physics and engineering depend only in part on command of mathematical logic. The complexity of its properties is far beyond that of the most subtle mathematics, and therefore of the most rigorous logic. The elucidation of its properties depends more on an educated insight into how a material object or machine may work, and this faculty is developed only by deep acquaintance with experimental facts.

The primary value of Euclid's work was in the limited educational region of mental training. It had also high practical value, but this was secondary and not in the most convenient form. Its particular form was related to the changes of structure in society which followed the imperialism of Alexander the Great. Society in Alexandria became more stratified than in earlier Greek cities. The leisured classes increased in numbers and wealth and could no longer be educated entirely by personal tuition.

The increasing separation between the classes was reflected in the development of mathematics. The primary emphasis was laid on logic, which is a verbal technique appropriate to the intellectual habits of an aristocratic governing class.

The technique of calculation, which had seriously declined from Babylonian to Athenian times, declined still further during the period of the greatest Alexandrian triumphs in pure science. The Babylonians had had a sexagesimal notation with place value and a symbol for zero in 1000 B.C. The Athenian Greeks had reverted to the use of letters for numerals. The chief numerals were represented by the first letters of their names. This was clumsy, but the Alexandrians replaced it by a far worse system. The numbers 1 to 10 were represented respectively by the first ten letters of the Greek alphabet. The

multiples of 10, from 20 to 90, were represented by the next eight letters of the alphabet. The hundreds, from 100 to 900, were represented by the remaining six letters, and three new ones adopted for the purpose. Calculations with these numerals are still more difficult than with those used in Athens. In addition, the appropriation of all the letters of the alphabet for particular numbers prevented the employment of unused letters as algebraical symbols for general numbers. Mathematicians did not care to invent numerous new symbols for representing several unknown quantities, and Diophantus, who lived about A.D. 300 and developed algebraical methods of solving equations, never used more than one symbol at a time to represent an unknown quantity.

The introduction of Arabian numerals centuries later assisted the development of algebra in several ways, one of which was the release of letters for use as symbols for unknown quantities.

The Alexandrian retrogression of arithmetic, which hindered the development of algebra, was due to at least two influences. Numbers could be handled by geometrical theory of ratio and proportion, whether commensurable or incommensurable. This method was logically exact though inconvenient in practice. It satisfied the intellectual demands of a leisured class. Simultaneously, the social status of arithmetical calculation, which had been relegated to slaves who worked with the abacus, was depressed further owing to the widening class differences.

The original governing class in Alexandria was Greek, and had imposed itself on an Egyptian population. The different origins of the upper and lower classes increased the width of social separation, and this remained after Jewish and polyglot elements had been assimilated into the educated class. Under these conditions, the study of those parts of mathematics (such as arithmetical calculation) which drew inspiration from the occupations of slaves languished.

20

ALEXANDRIAN MECHANICS AND PHYSICS

Aristotle's own studies in physics and mechanics were probably made while his thought was still dominated by Platonic theories. He had little time in his later years, after he had acquired a more submissive attitude to the results of observation, to apply his improved scientific method outside biology. But this work was not ignored, as pupils of his tradition applied the method to physics and mechanics. The results of their researches have not been preserved well.

Strato improved the physical atomic theory, and an Aristotelian whose name is unknown improved the theory of statics. The studies of the latter are reflected in a work on mechanics attributed to Aristotle, though composed after his time. This writer states that the phenomena of the balance may be referred to the circle, and the lever to the balance, while nearly all mechanical motion is connected with the lever. He remarks, also, that the motion of points on the radius of a rotating circle is the quicker the more distant from the centre, and that many marvellous results follow from the motions of circles.

The complete theory of statical moments and virtual work may be elaborated from those statements. For this reason, the Aristotelian tradition in mechanics has been rated by some philosophers higher than the Archimedean. It is true that this Aristotelian writer had a deeper insight than Archimedes into the philosophical principles of statics, but he did not elaborate his insight into an exact theory by experiment and calculation. In contrast, Archimedes derived an exact formula for the lever, but he appeared to derive it from postulates based on

instinctive knowledge, indeed on an aesthetic sense of balance, rather than observation and experiment. His result and his determination to apply mathematics to physical phenomena were progressive, but his attempt to reduce physics to geometrical deductions from postulates was regressive. It exhibited a lack of submission to observation and experiment.

The defect in Archimedes' conception of physics and mechanics was concealed by his extraordinary mathematical ability, but it was unconsciously reflected in the sterility of the researches of his followers. No one succeeded in extending mathematical physics very far along Archimedes' line, and his work did not exert its greatest influence until after the beginning of the Renaissance, when a body of new mechanical and physical observations had been collected by investigators under a different inspiration. The possessors of these new facts attempted to summarize them in mathematical form. They then began to feel the fascination of Archimedes' mathematical skill, and adopted his style of exposition.

The Archimedean mathematico-physical style was the most esteemed in the post-Renaissance period, and Newton adopted it in his *Principia* for the exposition of his discoveries. The limitations of the Archimedean style are illustrated by the effects of this choice. Newton discovered his results by processes more akin to a development of the scientific method used by Aristotle in his last years, but he expressed them in the Archimedean style. The use of this exquisite but sterile style was impressed by his authority on his immediate English successors, and was one of the factors which retarded the growth of mathematics and mathematical physics in England for a hundred years.

The works of Strato are lost, but references to them show that he answered Aristotle's objections to the atomic theory of matter by experiment and argument, and incorporated it into the Aristotelian tradition.

The results of the later Aristotelian studies of mechanics

and physics are reflected in the writings of Hero of Alexandria. He lived at some unknown date between the first century B.C. and the second century after Christ. He gave a proof of the formula for the equilibrium of a balance which depends on the properties of a pulley, and implicitly, though not explicitly, utilized the concept of the statical moment. The proof exhibits the mode of thought in the Aristotelian concept of statics, and is superior to the Archimedean, as it utilizes the properties of a machine which have been learned from experience. By virtue of its origin, it was closer to the engineer's interests, and gave deeper insight into the mechanical advantage of machines, and how it might be increased.

After this achievement, no considerable improvement in theoretical mechanics was made for more than one thousand years.

Another equally remarkable advance recorded by Hero concerns the theory of the vacuum. The early Aristotelians believed that a vacuum could not exist. They had observed that the force required to draw a wagon or ship was equal to the product of the speed and the resistance to motion. They concluded that if a force were applied to an object in a vacuum, it would change its place instantaneously owing to absence of resistance. This was absurd, and therefore the vacuum could not exist.

Strato criticized this theory, and concluded that an artificial vacuum could be produced. He probably confirmed his views by experiments with syphons. He extended Democritus' application of the atomic theory to the explanation of the properties of matter, and was the first to advance the doctrine of determinism in physics.

Strato's work on the vacuum assisted the students of mechanics to invent appliances involving the motion of fluids. Ctesibius in the second century B.C. invented a hydraulic clock and organ, and a force pump. His pupil Philo invented other machines, which will be discussed presently.

The writings of Strato and Ctesibius are entirely lost, and little of Philo's survives. The essence of the theoretical and practical results of their work on vacua has fortunately been preserved by Hero. He writes that every body consists of small particles, separated by still smaller vacua. In general there is no continuous vacuum, and everything is filled by air or water or some other substance unless it is held empty by an eternal force. If a measure of one of these substances is removed, an equal measure of another immediately flows in. A continuous vacuum is impossible without the exertion of a force external to nature, while a partial vacuum may sometimes be produced by artificial means.

These advances in the theory of mechanics and physics during the Alexandrian period were deduced from the study of machines that were already more than one thousand years old. The Egyptians were using the balance with unequal arms in 1550 B.C. in their shadoofs for raising water. These consist of a pivoted beam with a heavy weight at the short end, and a string and pot at the long end. The long end is depressed until the pot is submerged in a well. When it is released the short end with the big balance weight sinks, and the pot is raised. The difficult motion of upward hauling is converted into an easy exertion of downward pressure by the weight of the body. The syphon, which was utilized by Strato to prove the existence of the vacuum and the truth of the atomic theory, was used in Egypt in 1500 B.C. for drawing oil from storage jars. The Alexandrian science of mechanics, like Ionian philosophy, was based on criticism of the inventions and ideas of Egypt and Babylonia.

Hero discussed five machines which he considered simple because their modes of action could be explained in terms of the principle of the lever. These were the wheel and axle, the lever, the pulley, the wedge and the endless screw. The first of these was a Babylonian invention. The second, fourth and fifth were used in Egypt, and possibly invented there. The

pulley was widely used on ships in the first century B.C. These machines were chiefly valued for lifting weights and exerting pressures. The lever and the screw were employed in oil and wine presses, and pulleys and windlasses in cranes.

The helical screw, generally named after Archimedes but probably not invented by him, was used for raising water from the holds of ships. Water was raised by wheels carrying vessels. The wheel was mounted so that its lower circumference passed through a stream. As it revolved the vessels were filled and raised. The water began to run out as the vessels reached the higher circumference, and was caught in a channel or receptacle. Vitruvius in the first century B.C. described a wheel of this type about forty feet in diameter, with swinging vessels automatically emptied at the top of the circle, and driven by the flow of the stream against paddles on the circumference. More primitive wheels were usually driven by treadmills.

The ancient hand-bow was enlarged into a catapult machine in 400 B.C. It is thought that this was first done at Syracuse, where Archimedes devised many military machines one hundred and fifty years later. The propulsion in the improved catapult was derived from the stretching of elastic leather thongs, instead of the bending of pieces of wood. The catapult would throw stone balls weighing about five pounds nearly a quarter of a mile. As the leather thongs absorbed moisture, the catapults were sensitive to wet weather. Philo suggested that the thongs should be replaced by compressed air, or bronze leaf springs. He designed a compressed-air catapult, but there is no evidence that it was constructed, and modern attempts to carry out his design show that it is impractical, as the air is not compressed sufficiently to give the necessary expansive force. His proposal to use metal leaf springs was probably original, and indicates that springs were not generally used in antiquity. He mentioned the flexibility of Spanish swords as an illustration of the elasticity of metal.

Philo and Hero described many applications of the syphon for making entertaining contrivances, such as altar figures which poured libations continuously, singing birds, and cups which contained water at a constant level. They did not analyze the general principles which govern pressure in fluids and underlie the design of hydraulic machines, so they gave a wide variety of particular designs, but no general principles of design. They did not describe a vacuum pump, though this may have been used in antiquity for removing water from the holds of ships. The invention of the force pump is ascribed to Ctesibius, and was used in the form of the syringe, and elaborated into water pumps for fire extinction. A high-pressure water supply could have been operated with enlarged force pumps, but the pre-Christian ancients did not develop any general source of power greater than that provided by human muscles for driving machinery. Animals cannot be used for this purpose without heavy gearing, which had not been satisfactorily developed.

Water was distributed by gravity from a nearly uniform level in the reservoirs and aqueducts, owing to the lack of big force pumps. Small force pumps for supplying compressed air to organs were introduced in the second century B.C. The air was pumped under a vessel submerged in a tank of water. As the water was displaced from the vessel, the level in the tank rose. The volume of the vessel was large compared with the capacity of the pump, so a stream of air at nearly constant pressure could be obtained from the vessel and used for blowing the organ pipes. Hero describes a water organ played by depressing keys that operated slide-valves controlling the passage of air into the pipes. When the key was released, the valve was automatically closed by a piece of elastic bone.

The organ is a development of the bagpipe, and was operated by bellows before the introduction of the water-controlled pressure chamber. Bellows were used in Egypt at least as early as 1580 B.C. Hero described an organ driven

by the wind. The lever of the pump for supplying air to the pipes was lifted by spokes fixed into an axle rotated by a wind wheel. When a gust of wind rotated the wheel, the pump was operated and the organ played a tune.

Air was not the only gas used in Hero's appliances. He described various machines employing the pressure of steam. These included a reaction turbine. It consisted of a sphere mounted on a hollow axle. Steam was admitted to the sphere through the axle, and escaped through two bent tubes at the opposite ends of a diameter at right angles to the axle. The two tube exits pointed in opposite directions, and were parallel to tangents to the sphere. As the steam left the tubes, the steam and tubes moved in opposite directions with the same momentum. As the exit tubes moved backwards, they turned the sphere round and set it spinning on the axle.

Falling weights were used for operating puppet theatres mounted in boxes on wheels. As the weights fell inside the boxes, they rotated the wheels through string attachments. The box moved forwards and backwards, and puppets performed various motions on the top.

Automatic coin-in-slot machines were invented for supplying portions of holy water to temple visitors. The coin fell onto a lever, depressed it, and slid off. When the lever was being pushed down, it opened a water valve, and then closed it again after the coin had slid away.

The length of route marches was usually determined by professional steppers. Hero described a cyclometer containing several pairs of worm and tooth wheels for performing the task automatically. This was the only train of gearing used in antiquity.

Hero's chief occupation was probably surveying. The instrument used by the Egyptians and his predecessors for measuring small angles consisted of a four-pointed star bearing plumb lines at its corners. Its use was difficult owing to the swaying of the lines. Hero designed an instrument which

could be rotated in the horizontal and vertical planes by worm and screw gearing, and could be adjusted by water-level. No further fundamental improvement in the theodolite was made until the introduction of lenses.

Daylight time in Egypt and Babylonia was measured by the lengths of shadows cast by objects under sunshine. Night time was measured by water clocks. The Egyptian clocks were inaccurate, as the correct principles of design were not discovered, and the seasonal variations of the length of the night was generally ignored. Amenemhat claimed about 1550 B.C. to have made a water clock which gave correct night time throughout the year, assuming that the length of winter to summer nights was as 14 to 12. Water clocks were improved by the end of the pre-Christian era, but were not generally superseded until the seventeenth century after Christ. Vitruvius in the first century B.C. gave a vague description of a water clock in which the flow of water was regulated uniformly by a valve. The water ran into a cylinder and raised a float bearing a style, which passed across gradations on a vertical cylinder mounted above the tank. Twelve lines corresponding to the months of the year were drawn longitudinally on the cylinder. Then twelve curved lines were drawn around the cylinder corresponding to the twelve divisions of daylight or night, and were nearly horizontal but not quite, as the length varies with the season. The correct length of gradation for any day could be placed opposite the style by rotating the vertical cylinder, and fixing it according to the date.

21

ROTARY POWER MACHINES

There is no record of the origin of the most pregnant technical invention ascribed to the five centuries before Christ. This is the invention of revolving grindstones for making flour. The Volsinians are credited with it, though on doubtful authority. It was probably made in the fourth century B.C. Previously, grain had been pounded in mortars with a stone. The new method consisted of feeding grain between two stones, one of which revolved steadily over the other. Owing to the removal of the need for lifting and grinding, as with the pounder, the weight of the moving stone could be increased. Further, as the movement of rotation was uniform it could be performed by a simple machine without intelligence. The revolving grindstones provided the first good opportunity for the application of power to rotational machinery. The first definite reference to the querns, or revolving grindstones, is given by Cato the Elder, about 200 B.C. In this reference he also states that they were worked by asses. It is remarkable that the revolving grindstones should be associated with the use of power. The first references to hand querns occur later. A lighter and more efficient form consisting essentially of two grooved discs, one of which rotated on the other, was introduced just before the Christian era, and was worked by hand. It seems that the introduction of heavy rotating machinery driven by animal power was contrary to the tendency of the time, and inventive ability was applied to the improvement of the efficiency of the quern, so that the amount of motive power required to operate it was not more than that supplied by human muscles.

While this regressive movement occurred, it had secondary progressive effects. The improved hand quern was advantageous to the independent peasant who could not afford an animal to grind his flour. But as the number of independent peasants steadily declined with the age of the Graeco-Roman era, the chief effect of the improvement was to arrest the development of power-driven machinery.

The obscurity of the invention of the heavy animal-driven quern suggests that it was made in a relatively free non-Greek agricultural community, and its original form was rejected by the Graeco-Romans because it was not consonant with a slave system of production. The Graeco-Romans used their ingenuity to remove the use of animal power from the invention, in order to adapt it to slave power.

The application of the water wheel to corn grinding ma have been invented in the first century B.C., though the firs description of such a machine occurs in Irish laws written i the fifth century after Christ, in the time of St. Patrick. Ron depended on water mills for flour at the end of the fourth ce tury. Windmills were not used for grinding in Europe un the twelfth century. There are Arabian references to win mills in the tenth century, and it is possible that windmil were used for rotating prayer wheels in Tibet at an earlie date. Hero's account in the first century B.C. of a windmill for driving an organ has already been mentioned.

22

GREEK ALCHEMY

There is virtually no evidence that the pre-Christian Greeks made any considerable contributions to experimental chemistry. They adopted in general the processes for preparing metals, glass, pottery, dyes and medicines which had been invented in previous millennia. Very few accounts of these rocesses have survived. As urban civilization grew more mplicated, the value of a knowledge of metallurgy steadily :reased. It provided the metals used as currency in an exading system of trade, besides those used in improved tools d weapons. The stability of the new financial structure dended on the quantity and quality of gold, silver and copper t into circulation. Authorities guarded the technical knowl-ge of refining and adulteration of metals very carefully, to prevent counterfeiting and inflation. They also wished to exploit the economic advantages of secret processes. These motives combined with the lack of respect for technique as a part of culture to prevent the publication of accounts of metallurgical processes. Diocletian issued a decree at the end of the third century after Christ that all ancient books on the making of gold and silver should be destroyed.

Two manuscripts of this period, dealing with the methods of making alloy substitutes for precious metals, and paste and glass substitutes for precious stones, have survived. These were written in Greek on papyrus by an Egyptian chemist. Like the fragments of technical literature which have survived from much earlier Egyptian periods, they are notably free from credulity, and their author did not believe that he could

fabricate genuine precious metals and stones. His technical processes were probably little more advanced than those used in Egypt two thousand years earlier. The pre-Greek tradition of applied chemistry continued beside the Democritean theory of atoms and the Aristotelian theory of the elements. The development of the idea of transmutation which occurred in the second century after Christ owed much to the Aristotelian theory, but less to the atomic theory, though not in conflict with it. According to the atomic theory, all matter consisted of various combinations of one sort of primitive atoms. It followed that different kinds of matter should be capable of resolution into the primitive atoms, and recombined in any desired manner. For instance, the matter of common metals should be capable of resolution into the primitive atoms, and these should be capable of recombination into gold. Transmutation seemed a reasonable deduction from atomic theory. The chief inspiration for its pursuit was not the ideas of Democritus nor Aristotle, but the occult idea of magical change.

Systematic laboratory research on transmutation gradually developed. The Egyptian metallurgists probably did not distinguish between the foundry and the laboratory. They noted unusual phenomena which happened with materials being prepared for definite orders, and adapted these for use in the future. Innovations were usually discovered during the process of manufacture, and not by special investigation. Laboratory research, in which processes themselves are investigated, and the product is of no immediate importance, was chiefly an Alexandrian invention. The research rooms of the Museum encouraged the development of laboratory research, and its results in mathematics, astronomy, biology and mechanics have been described. It did not noticeably affect chemistry until the second century after Christ, when important improvements in chemical apparatus were made. Maria the Jewess described effective forms of laboratory apparatus for heating,

melting, filtering, distilling and subliming materials. The late Alexandrians who followed her developed the use of the glass flasks and retorts and other pieces of apparatus which have since remained typical of the chemical laboratory.

The late Alexandrians may be credited with the invention of systematic experimental chemistry in their attempts to manufacture gold. Though the effective parts of their new science, known at first as alchemy, were chiefly derived from the practical tradition of Egyptian metallurgists, other parts were derived from magical and mystical sources. The transformation of one thing into another by magic is a very ancient idea, and is always attractive to the undisciplined mind, as it seems to accomplish something without doing any work.

Why should experimental chemistry have been born with mystical elements when its forerunner in applied chemistry was notably naturalistic, and the sciences of experimental physics and biology had already, through several centuries, made some progress?

The later appearance of systematic experimental chemistry may be due chiefly to the disagreeable and therefore disreputable nature of its processes. The Egyptian scribe of 1200 B.C. who remarked that the metallurgist "stinks worse than fish-spawn" has already been quoted. Research in pneumatics and hydraulics became reputable sooner, because its material is less disagreeable. In addition, elementary chemistry is more complicated than elementary physics, so progress in it is more difficult.

The acceptance of chemistry as reputable in the late Alexandrian period was influenced by many factors. The rise of Christianity improved the repute of the slave and craftsman, and this tended to improve the repute of his disagreeable work. Leisured persons could make chemical investigations without losing social status. This progressive movement was accompanied by a regression towards magic. The revival of the prestige of magic, which was connected with the rise of

the transcendental religions of Christianity, Gnosticism and Neo-Platonism, all of which contain magical elements, strengthened the repute of the magician, and this in turn made his disagreeable practices reputable. The restoration of magic was not entirely regressive, as it strengthened the belief in the possibility of change and transmutation.

The earliest alchemist whose works have survived was a Gnostic named Zosimos. The Gnostics believed that there was an invisible world behind the sensible, and that it was peopled with living abstract entities. They were convinced that they had access to this invisible world, and could enter it after suffering mysterious changes. These were analogous to the chemical changes of materials. They believed, accordingly, that the study of chemical change was a guide to those changes which placed their own spirits in communication with the sources of ineffable knowledge.

Zosimos' works consist of ecstatic visions which may be symbolic descriptions of chemical changes, interspersed with considerable descriptions of chemical apparatus and operations, and injunctions to secrecy. He describes the preparation of mercury and arsenic, and states that arsenic will convert copper into silver. This was evidently a reference to the silvery appearance of copper arsenide. He knew that sugar of lead was both sweet and saltlike, and could be prepared by heating litharge with vinegar.

He discussed the merits of glass and pottery for apparatus, and reported that the best glass vessels came from Askalon in Syria. He joined apparatus together with clay, fat, wax and gypsum, and he used the sun, sand-baths, water-baths, fermenting manure, and furnaces as sources of heat.

The founder of Neo-Platonism was Plotinus, who lived in the third century after Christ. He believed the material universe was a partial manifestation of a transcendental world of spirits. The stellar motions, in particular, had transcendental significance, and revealed aspects of the future. The spirits existed

in harmony and sympathy, and the aim of the disciple was to detach himself as much as possible from matter, which was the principle of evil, in order to join this harmony. Neo-Platonism emphasized the ideas of sympathetic action and action at a distance, and the difference between occult and manifest properties. The Neo-Platonic alchemists investigated the properties of matter in the same manner as astrologers studying the stars. They hoped to learn occult properties from the study of material manifestations.

These ideas permeated alchemy and were not subdued until the seventeenth century. Experimental chemistry developed during the decline of Graeco-Roman civilization, when the movement against slavery was beginning. The decay of the old social system assisted the chemical experimenter by reducing the social prejudices against him, but it also destroyed much of the healthy part of the old philosophical criticism, and loosed clouds of delusive ideas. The renewed contempt for the material world again weakened the respect for fact and observation, and hurt more than it helped science. Partington has concluded from his remarkable study of the origin of applied chemistry that "the knowledge of the use of materials in the Classical Period, which usually forms the starting point for the historian of science, is almost wholly derived from much older cultures. It represents, in many cases, not an original and vigorous development of national genius, but a decadent form of craftsmanship which had existed for a period often as long as that which now separates us from the best days of Greece and Rome. Just as the modern industrial period has ruined the traditions of craftsmanship, so the irruption of the people of the Iron Age broke the continuity in a traditional use of materials which had developed almost without a break from the period of the Stone Age. The essential methods nevertheless continued with little alteration, as in some cases, such as the art of the potter, they do to the present day."

Graeco-Roman civilization contributed relatively little to ex-

perimental chemistry, but it invented or developed the atomic theory and the germ of the theory of phlogiston, which more than a millennium later proved of fundamental value in the creation of modern chemistry.

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ALEXANDRIAN MACHINERY WITHERS

A review of the technical inventions known by the end of the second century after Christ shows that the concepts of a large number of machines, including force pumps, automatic slot machines, trains of gearing, water wheels, windmills, rotary grinders, and even the reaction steam turbine, had been discovered. These machines embody many of the mechanical principles which have subsequently been adopted in productive machinery, but the Graeco-Romans contributed little towards the process of adapting them to productive use.

Hero describes seventy-eight machines in his treatise on pneumatics. Nearly all of these are temple furniture, and resemble the equipment of the temporary fun-fairs opened in shops on short leases in busy modern cities. He describes ten syphon appliances for producing illusions of the type of the apparent conversion of water into wine. A flow of wine is produced from one vessel by pouring water into another. There is also a series of appliances depending on the expansion of air by heat. Fires are lit on hollow altars, and as the air inside expands, it passes through concealed pipes and pushes libations of liquids onto the flames.

The expanding air inside the altar may be made to open the doors of the temple automatically. This was done by arranging that the hot air should force water through a syphon into a bucket attached to a rope. As the bucket filled, its weight increased, and dragged on the rope, which was wound round axles operating the doors. These were gradually swung open as the bucket descended. When the fire on the altar went out,

the air inside cooled, and the water was syphoned back from the bucket. The bucket automatically returned to its original position through a counterweight, and at the same time the temple doors were closed.

The method of supporting spheres aloft by jets of steam, analogous to that used in modern shooting booths, is described. There are designs for fountains driven with air expanded by the sun's heat, automata which drink and sing, and hot-air blasts which issue from a dragon's mouth. The supply of mixed air and steam for the blasts may also simultaneously make a blackbird sing and a Triton blow his horn.

This series of appliances, including automatic theatres, was designed to amuse, delude and impress the mass of worshippers at the temples. It was a contribution towards the technique of managing the ignorant multitude, especially of Alexandria. The social significance of this machinery is seen in its contribution to government rather than production, and in commerce. The automatic slot machine for selling portions of holy water shows that the commercial exploitation of superstition by machinery had reached an advanced stage.

The numerous temple machines were probably operated by attendants on payment of a small fee from the worshippers, and the invention of a device for replacing the attendant and saving the cost of his upkeep could have been achieved only after the mechanization of temple life had passed through many stages of development.

The temple machinery was designed to produce motion rather than do work. Reuleaux has explained that moderns are unconsciously inclined to assume that machines always combine force with motion. He believed that the production of this combination is less primitive than the production of movement alone, and for this reason has asserted that the fire-drill is the first machine, and was invented before the lever. The child is interested in toy windmills, or anything which moves, long before he becomes interested in the possibilities of these con-

trivances for doing work. He concluded that this is the reason why the uninstructed are so apt to believe in perpetual motion, and why the first machines, in his opinion, were not concerned with the exertion of great forces. The perception that great forces could be exerted by machines occurs at a late stage in their development. According to this view, Alexandrian windmills and steam turbines were early developments of rotary motions which had not evolved beyond the stage of appeal to primitive wonder, in which pure motion is admired, as in the myths of Mercury, Icarus and Ariel. They were designed to produce motion, and the power obtained from them was a secondary interest. The division between power and motion is reflected in Hero's division of his works into mechanics and pneumatics. The first is concerned with forces, while the second is concerned with motions.

The first source of power was human muscle. According to Reuleaux, the method of multiplying human power by the lever was invented after the drill for producing fire by motion, in which muscular power is secondary. The first rotary machines primarily designed for doing work, such as the wheel for lifting water and the quern for grinding corn, were driven by human muscles. The idea that rotary machines could be used for multiplying human power was applied in the screw press.

The development of machines for deriving motions from human power occurred slowly through many millennia. The conception of animals as a source of power is more abstract, and came later. The concept of inorganic power in the form of water is still more abstract, and was held as yet uncertainly by the end of the Roman era. The classical world never succeeded in formulating the concept of pure power abstracted from its medium of operation, such as human or animal muscles or falling water.

The substitution of animal for human power involved important changes in the conceptions of power, which had to

be conceived as something that might exist independent of the human body and will. This considerable psychological difficulty was accompanied by technical difficulties of employing animal power which were never adequately solved in classical times. Lefebvre des Noëttes has made a study of the methods of using animal power which has yielded very important results. He has shown that the Greeks and Romans never discovered how to design an efficient harness for horses. They placed the collar high on the neck, and attached the traces to the collar at the back of the neck. If the horse was driven hard, it was choked by the pull on the collar and, owing to the high point of attachment, was reared up onto its hind legs. Consequently, it could not exert more than a third, or less, of its possible effort. In efficient harness the collar rests on the shoulder-blades, and the traces are attached at each side of the body, just above the fore shoulders. This improvement was not used in Europe until the Middle Ages, though the Chinese had progressed towards it at an earlier date. The Graeco-Romans also failed to invent iron horseshoes. This limited the use of horses for transport on hard roads.

The horse is about as strong as ten men. Owing to the inefficiency of the classical harness it could not usefully exert more than one-third of its strength, and was effectively not stronger than three men. As it was far less intelligent and manageable (the proverbial definition of unmanageability is the act of "kicking over the traces"), there was on the whole not much advantage in employing it as a source of motive power. In addition, horses eat more than men, and the dry lands around the Mediterranean are not rich in fodder. This difficulty did not arise in the rich grass lands of northwestern Europe, and when civilization developed there in the Middle Ages the horse had a more important part in technique than it had in classical times.

The substitution of animal for human muscular power was not very easy in Mediterranean countries. Nevertheless, the

failure to invent efficient harness in classical times is due far more to indifference to the problem rather than intrinsic technical difficulties. A moderate social demand for the reduction of human labour would have inspired the not very difficult improvements of harness which would have made animals far more efficient sources of power, and this would have accelerated their substitution for human beings.

Animal power could not be exploited without the development of efficient and strong rotary machinery, and as its adaptation was retarded, the development of efficient forms of heavy gearing was retarded.

The backwardness of the development of efficient heavy gearing in turn retarded the search for sources of power greater than that provided by animals.

The technical difficulty of converting pure motion machines such as Hero's windmill into power-producing machines was too great to be overcome without the intermediate development of the use of animal power. As this was not accomplished satisfactorily, the technician did not evolve the moderately heavy rotary machinery suitable for the utilization of animal power, and which provides the basis of mechanical development for the successful utilization of greater forms of power.

Usher has commented on the importance of the psychological difficulties in technical invention, and ascribes the slowness of the development of technique in classical times to these, rather than the prejudice against manual labour in a society based on slavery. He has explained that primitive inventions occur in the sphere of perception. The inventor solves his problem by modifying a tool or process whose parts are all before him. He may scarcely be aware that he has solved any problem, and the modification may be slight in itself though technically of great consequence. A very great invention such as the cultivation of plants may well have come into existence through a series of almost unconscious actions. Owing to the obviousness of such improvements to all ordinary persons after

they have been made, their invention is not rated highly, and the inventor is not highly esteemed.

The notable poverty and unreliability of the early history of invention, and the failure to record the names of early inventors whose work has created the main part of civilization, is partly due to the apparently trivial nature of inventions which occur in the sphere of perception available to all normal men. They did not seem very remarkable at the time, and neither the inventor nor the process of technical improvement gained much prestige from them.

The situation changed when technical invention passed from the realm of perception into that of conception. James Watt did not invent his improved steam engine by modifying the parts of a Newcomen engine. He invented his engine with a separate condenser in his imagination, on the basis of a knowledge of the abstract theory of latent heat, after engaging in the repair of a model Newcomen engine.

Those without abstract scientific knowledge could not understand the explanation of the superiority of the Watt engine, so they found the invention far more impressive than those made in the sphere of perception, and naturally remembered the inventor's name. But inventions made in the imagination on the basis of abstract scientific ideas are not necessarily more important than those made in perception. The invention of the wheel is more important than the Watt engine.

The prestige of the profession of invention has, however, risen with the transfer of the process of invention from perception to conception, and from the sphere of manual to mental work.

The perceptional nature of early invention helps to explain the lack of prestige of technical processes. It did not seem to be clever. But cleverness is one only of the tests of value. Was the invention useful, and of benefit to humanity, and if so, did the inventor receive fair reward and esteem? Classical society

was not much interested in these questions because its small class of free men could live comfortably without arduous work, and could seize the benefits of inventions made by slaves without engaging in invention themselves.

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THE INFLUENCE OF THE SOCIAL REPUTE OF MANUAL WORK

The thesis that technical invention advanced slowly in classical society because at that time it involved the exercise of processes in perception rather than conception, and therefore was deemed trivial and beneath the attention of educated men, implies that technical invention advanced slowly because it was easy. While this conclusion probably contains an element of truth, it does not offer a complete explanation, for it is difficult to believe that invention was not cultivated because it was deemed trivial. Humanity does not desist from easy activities unless prevented by external influences. The failure of invention to develop rapidly while almost entirely in the perceptual stage suggests that the influences which were retarding the development were not inherent in, but external to, the process of invention. Inherent difficulty also fails to explain some aspects of the slowness of the early development. If consciousness of the inherent difficulty of technical invention were the retarding influence, the fame and historical record of the inventors in classical times would be far greater, as the magnitude of their achievement would have been better appreciated. Neither the ease nor difficulty of invention furnishes an adequate explanation. Inventions are of virtually infinite variety, and their production presents many sorts of problems. The production of successful inventions in different fields needs different qualities, and will not be achieved unless persons with those qualities exist. The slowness of invention might apparently be due rather to the lack of inventors with suitable tal-

ents. This would not explain a general failure of invention, as it is improbable that the stock of human inventiveness varies much in different periods. An analysis of the fundamental problems involved in inventions and the mode of thought of their inventors would provide information of great value, especially for the interpretation of the histories of these inventions and inventors, but the detailed picture of particular cases in any age should not be allowed to obscure the outlines of the general conditions of invention. When inventions and inventors of nearly all varieties are sterile the cause will more probably be found in general features of the age than in peculiarities of current inventive problems.

As the inventors of the classical period were working with real objects in the sphere of perception, they were manual workers, and they exercised their inventive abilities under the conditions which governed manual work. An examination of these conditions will reveal some of the influences which bore on an inventor in that period. Manual workers were slaves. As they included nearly all the inventors, most of the technical inventions of the classical period were made by slaves. This embarrassed some of the philosophers, such as Posidonius, who asserted that technical inventions were made secretly by philosophers and given by them to slaves in order to conceal acquaintance with the disreputable processes of manual labour. This conventional opinion was denied by Seneca, who contended that technical inventions were made by craftsmen, and instanced central heating through hollow walls by hot air, and shorthand, as inventions made by slave craftsmen in his own day. These important inventions made under conditions of slavery demonstrate the vitality of human inventiveness, and show that creative work may be done without personal freedom. The belief that dictatorial social systems must rapidly collapse owing to the decay of technical creativeness in the absence of freedom is misleading. The collapse occurs ultimately, but sometimes not for centuries.

The condition of gold miners in Egypt in the first century B.C., or rather earlier, has been described by Diodorus Siculus. "The kings of Egypt collect those condemned for crimes, captives taken in war, persons ruined by false accusations, and therefore sentenced to imprisonment, sometimes alone, sometimes with all their families, and condemn them to the mines, thereby at once inflicting punishment upon the sentenced, and extracting vast profits out of their labours. Now these convicts, in great numbers, all in fetters, are kept at the works, not merely all day but throughout the night also, getting no intermission of labour, and carefully guarded against escaping. For guards are set over them of foreign soldiers, and speaking a different language, so that it is impossible for the prisoners to corrupt any of their guards by speech, or by motives of humanity. The ground containing the gold they first heat with long-continued fire, and so render full of fissures, before they apply manual labour to it; but the rock that is soft and capable of yielding to moderate labour is cut down with the tools stone-cutters use by myriads of these poor wretches."

The strongest men broke the marblelike rock with iron pickaxes, and carried lamps on their foreheads in the dark galleries. They "bring to the floor the fragments of the cut rock, doing this under the lash and cruelty of an overseer." Boys meanwhile crept beside, and picked up the broken mineral and carried it to the mine's mouth. "Here those above thirty years old receive from them a fixed measure of the broken ore, and pound it in stone mortars with iron pestles." The women and older men, working two or three to a machine, ground the granulated ore from the mortars in hand-mills, until it was as fine as flour. One group of skilled workmen washed the gold out of the powder, and another melted it into ingots.

The extent of slavery increased with the growth of the Alexandrian and Roman Empires. The Romans were originally farmers, and preserved a sentimental regard for the land and its processes after they had become urbanized. The soldiers of

the early Republic, whose victories provided the basis of Roman power, were farmers. They subdued Italy and Greece, and then the whole of the Mediterranean world. These fighting farmers were absent from their farms for periods of months and ultimately of years. Their land required cultivation in their absence, and they naturally arranged that this should be done by the numerous captives made in their campaigns. The early free farmers were largely replaced by slave labourers. This movement was accompanied by a concentration in the ownership of land. Many of the original individual owners were killed in the incessant wars on the frontiers, and their lands were left under weak protection. The survivors were promoted in military rank, and grew rich with booty. They bought the old small farms from the families of their slain colleagues, and amalgamated them into larger units. The size of these estates led to the accumulation of large quantities of raw materials, and the creation of an appropriate capitalistic system of trade. The Romans exploited the estates by slave labour working under slave bailiffs. The system did not grow without resistance from the expropriated smaller farmers. The Gracchi led a great campaign against the movement at the end of the second century B.C., but they were struggling against a fundamental social movement, and were defeated. The degree of this development by the first century after Christ is reflected in the social criticisms of Seneca. He complained that estates had grown to the size of provinces through the gradual purchase of neighbours' fields by fraud or gold. Between 150 B.C. and A.D. 250, three-quarters of the population of the Roman Empire were slaves, and at the market in Delos slaves were sold at the rate of ten thousand a day. The later campaigns did not provide a sufficient supply of slaves, and the shortage was remedied by unofficially organized kidnapping and piracy.

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THE INFLUENCE OF ROMAN SOCIAL CONCEPTIONS ON SCIENCE

The Roman conquests were substantially complete by the time of Julius Caesar's death. Augustus devoted his energy to the consolidation of the gains. This situation influenced the direction of the development of Roman society, including that of the institution of slavery. The number of captives made in the campaigns decreased, so the replacement of slaves by fresh captives became less easy. Romans were compelled to pay more attention to the production of slaves at home, and as Gibbon has written, they were obliged to use "the milder but more tedious method of propagation." This involved the encouragement of family life, and the increase of stability and comfort in the social conditions of slaves. These changes were reflected in new laws. The power of a master over his slaves was not limited by law under the Republic, but an increasing number of legal limitations were introduced under the Empire. Augustus and his successors were also much concerned with the decline in the numbers of the Roman families. They made numerous laws encouraging the increase of families in all strata of the population, and eased the regulations of manumission. A complicated caste system of nobles, free men, freedmen and ranks of slaves was evolved. A slave received payment which was held by his master but protected by the law. This payment, or *peculium*, included tips, money, land, houses, shops, rights, and the possession of inferior slaves, the analogues of the gentleman's gentleman.

The highest ranks of slaves were sometimes richer than

their masters, and included wealthy doctors, captains of vessels, teachers of science, and bankers' agents. They could use their peculium for the purchase of freedom. They then became freedmen, and could enjoy such privileges as were not restricted to the free-born. A few freedmen ultimately rose to be senators, knights and provincial governors, and many qualified for the admired civil service. The son of a freed slave was free-born, so in two generations the family of a slave could theoretically rise to any position in the state.

The slave did not usually differ in appearance from a free man. He wore the same type of clothes. The Senate rejected a proposal for a slave uniform on the ground that it would impress slaves with their own numbers and potential power in the state. Fascist uniforms have been suppressed in recent times in democratic countries for analogous reasons.

Under a good master slavery could be a school for qualification as a capable citizen. A slave could learn writing, calculation, trades and agriculture, and, according to Cicero, could save enough to purchase freedom in six years. If he was originally a barbarian captured from a German forest, he became trained in Roman habits, and acquired a more advanced tradition. In this perspective, J. L. Myres has remarked that "slavery is a compulsory initiation into higher culture." It was not without value as a training for regular work, and an instrument for unifying society.

The finely graded structure of Roman society under the Empire was held together by punishment and force. The Romans believed that slaves were unable to tell the truth except upon the rack, so torture was the normal method of their legal examination. Owing to this circumstance, slaves were often trusted better than free men with large sums of money and big commercial transactions. The owner felt he could more easily get at the truth by the torture of slaves than the verbal examination of free men, if any chicanery was suspected.

The more fortunate ranks of slaves belonged to colleges

which consisted of social clubs, craft guilds and burial societies. They enjoyed feasts, parties, and entertainments. The colleges included freedmen who mixed with the slaves on an equal social footing.

As Martial writes: "You don't realize the cares of a master, or the advantages of a slave's life. You sleep well on a rug; your master lies awake on a bed of down. You salute no one—not even your master; he salutes in fear and trembling a number of patrons. You have no debts; he is burdened with them. Do you fear the torturer? He is a martyr to gout."

A similar attitude was expressed by a distinguished German engineer during a visit to London in 1939, when he said to an English friend that the beautiful feature of life in Germany under National Socialism is that it is no longer necessary to think. One has only to obey.

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THE INTERNAL COLLAPSE OF A SOCIAL ORDER BASED ON SLAVERY

Roman slavery in the peaceful period of the Empire was not entirely brutal. The close relations between the master's family and his slaves could not have continued, and the complete social structure could not have survived unless there had been some elements of social adjustment and toleration between owner and slave. The slaves' possibilities for acquiring wealth and comfort explain why they made important inventions of the sort mentioned by Seneca, even though such contributions did not remedy their lack of human dignity.

No civilization was possible at the time without slavery, because the machines which could replace slaves had not yet been invented. There was a consciousness that slavery was an essential part of the contemporary social system, and this made owners look after slaves carefully, just as a modern owner carefully tends his machinery. Modern negro slavery, unlike classical slavery, has been entirely anti-social because it has not been essential to the productive system of modern society, which possesses efficient machines. The social atmosphere of later Roman slavery was probably not so offensive, owing to the recognition of a genuine element of value in the institution.

The defects in social psychology produced by slavery cannot be exterminated, even if the system may be economically justified in ancient societies. Dio Chrysostom, who lived in the second century after Christ and was adviser to Trajan, was the first Greek writer to assert that slavery is contrary to the law of nature. He said that the chief characteristic of slaves is that

they are quite incapable of helping themselves. This lack of initiative is reflected in the remarkable fact, noted by R. H. Barrow, that in spite of the immense remains of Roman history and inscriptions, no Roman slave has left a sketch of his life and working conditions. A class which comprised three-quarters of the subjects of Rome has left no autobiographical account of its mode of life. Many slaves had sufficient means and literary skill, but none believed that his life was worth describing.

A large number of gravestones of slaves bear inscriptions which show their owners' concern with social status. The problem of status produced an inflammation in the consciousness of the members of the minutely graded classes of Roman society. Ambitious and able slaves were preoccupied with the acquisition of freedom and the conveyance of manual tasks to inferior slaves. The preoccupation with status was inimical to the objective study of manual processes and the phenomena of nature. This influence was one of the causes of the decline of science in Roman society.

Opposition between science and slavery is perhaps reflected in the attitude of Pliny. This indefatigable student of natural history was liberal, and made special arrangements to secure the manumission of many of his own slaves and those of his friends. But advocacy of a liberal operation of the system did not indicate disapproval of the principle.

The philosophers of classical antiquity offered an explanation for the establishment of their society on a basis of slavery. Aristotle suggested that humanity was divided into two sorts, one which was fit to govern and the other to produce. The first sort only was entitled to social rights and privileges, and should be restricted to rulers and soldiers. The second sort was necessary to society but was not entitled to have any rights in it, because, in his view, producers were not of value to society through their own will, but only through the directing intelligence of the governing class. The rôle of producers was purely passive, and disappeared if the active principle of gov-

ernment was removed. The passive producers were not a part of society, though necessary to it, just as a field which produces grass is necessary for supporting a cow, though not part of the cow. Aristotle did not hold this theory consistently, as he ordered his slaves to be freed when he was dying.

The lack of contact in feeling between the ruling classes and slaves is illustrated even by the noblest writers. Cicero discusses in his treatise *On Duty* whether one should lighten a ship in a storm by casting slaves or a favourite horse overboard, and concludes that the slaves should go first. He asks whether slaves should be fed in time of scarcity. Cato the Elder recommended that worn-out slaves should be sold or allowed to die.

The lack of regard for slaves and its degrading effects are strikingly illustrated by Graeco-Roman sexual conventions. Farrington has remarked that Pindar, Horace and Paulinus of Pella, who were respectively Greek, Roman and Christian, and who flourished at the beginning, middle and end of Graeco-Roman power, recommended the prostitution of slaves. Horace and Paulinus advised young men to satisfy their appetites with slaves rather than free women or men, who might subsequently prove troublesome.

Those men and women, including clerks, foremen and craftsmen, who were engaged in productive and manual work, and were familiar with the problems of technique, were slaves and subject to the discouragement of degradation. The individual cannot invent or discover without optimism, as he will not try new experiments unless he believes they may be successful. If he has no hope in life, he is without any source of constructive energy. The most remarkable feature of the retardation of the rate of technical advance in classical society is not the decline of many parts of technique in Roman times to an almost static condition, but the continuation of small positive improvements. Inventiveness was not entirely repressed in classes of technicians that remained enslaved for millennia. The failure of

these ages of slavery to repress invention entirely suggests that men have large resources of delusive optimism, which encourage improvement even when it is of no advantage to them; or that the tendency to invention is very tough and will endure the utmost discouragement, and that men will strive for betterment against all obstacles. If the latter explanation is the truer, it will encourage those who pursue progress.

The concentration of the ownership of land in the Roman Empire produced vast concentrations of wealth. These provided the governing class with the means for fantastic dissipation, and helped to extinguish their inspiration for invention, as they could satisfy their desires without any creative effort. The division between the highest and lowest members of the population became wider, and initiative on the part of the slave craftsman more pointless.

The government of this society based on slavery was chiefly concerned with the regulation of the relations between the members of the minority of free men. It had no primary interest in the processes of production, and accordingly developed law rather than science. It was not primarily interested in the development of productive machinery because it had vast supplies of human machines, described by Varro as "articulate instruments."

The administration of a slave empire which grew continually larger while methods of production remained static ultimately proved too much even for Romans. The bureaucracy became top-heavy, and absentee landlords lost touch with the problems of cultivation. The fertility of the soil in many areas was exhausted, and the threads of the system fell apart.

The Romans had brought many lands under large-scale administration and cultivation. The descendants of the slaves that they had attached to the new estates acquired a little freedom after the Imperial power had decayed, and became the ancestors of the medieval serfs. These peasants had a very low

standard of life, but they did not forget the small technical improvements added during classical times.

The Babylonian and Egyptian inventors were less brilliant than their neolithic ancestors. The Greek technicians achieved less than the Babylonians and Egyptians, and the Romans still less than the Greeks. The Roman failure is perhaps connected with their adoption from the Greeks of a highly developed system of slavery. The peak of the creative effort of the Greeks occurred while their neolithic tradition was still fresh. The Romans passed more suddenly from small farming to highly developed slavery. They adopted this from the Greeks and were unable to criticize its products and ideas with the independence with which the Greeks had examined the products and ideas of their predecessors. Their proximity to the Greeks hindered their assimilation of Greek science because it prevented them from viewing it objectively, so they turned against it. The Romans were far more ignorant than the Greeks, but they had conquered them. They attempted to excuse their ignorance by despising the works of those whom they had conquered, and they asserted that they need not study science when it could be obtained from an enslaved Greek. Virgil wrote that war and government were the proper occupations for Romans. The Roman victory increased the resistance to the growth of science. The Romans devoted their ability almost wholly to the development of law and administration; the sole section of culture in which they excelled the Greeks.

This one-sided development encouraged a disastrous opposition between science and administration, between the creative and the organizing forces in civilization, which still persists, and is one of the causes of modern social disorder.

The Franks, Germans, Goths and other barbarians who succeeded the Romans were in a more fortunate position. Like the Greeks who succeeded the Babylonians, they lived in tribes of small farmers which preserved some of the freedom of

neolithic societies, and they were able to view Roman society independently, while inheriting many of its technical accomplishments. They did not succumb entirely to the Roman system, and did not adopt complete slavery.

27

THE ROMAN ECONOMIC SYSTEM AND SCIENCE

The economic disadvantages of slavery were noticed by a few observers in antiquity. Hesiod commented on the economic advantage of free labour for some tasks, and in the first century B.C. Varro wrote that hired labourers were more profitable than slaves for work in malarial swamps. Similar observations were made in the Southern states of North America during the period of railway construction. Hired Irish labourers were less expensive than negro slaves for the construction of railways through swamps, and thousands of them died at this unhealthy work.

The Romans had adopted slavery during their period of military expansion. A system of production based on slavery was particularly appropriate in this period, when military took precedence over civil requirements. When society had settled under the Empire, direct economic interests exerted more influence. Landlords at peace were more interested in deriving the maximum profit from their estates than in the organization of society for effective military action. They tried to increase profits by reducing the costs of production, and presently noted that under peaceful conditions, when slaves must be replaced by propagation, that the costs of slave labour might be higher than those of free labour. Without recognizing this fact very clearly, the Roman rulers passed laws for increasing the proportion of free labourers. Julius Caesar decreed that the proportion of free labourers on the land should not be less than one-third. The conditions of an increasing number of slaves were gradually improved until they approximated to

those of free labourers. This change was due far more to the influence of economic motives than to Christian propaganda in a society whose aims had changed from conquest to defence and economic development. From the second century after Christ, free labour was slowly but steadily encouraged. Many freed slaves tended to enter trades and professions, and the number of free small farmers increased. The conditions of the workers employed in the factories of the prosperous owners of estates did not improve in proportion. Most of these remained slaves. The social conditions of those who used machines continued to be bad, even when those of other working classes improved.

The pattern of Roman productive organization was the self-contained estate. The Roman aristocrat aimed at supplying all his needs from his own estate. He built small factories for supplying local needs, and did not usually aim at manufacturing for export. Very few Roman factories contained more than fifty slaves.

This idea of house economy influenced the aim of the economic development of the new provincial towns. They also were self-supporting, and did not manufacture much for export. The Roman cities were not mainly industrial, like modern cities. They were centres of administration and military headquarters, more like modern county towns with barracks. The offices and town houses of the chief officials in every province were in the provincial capitals, while their villas were in the country. The provincial cities were imitations of Rome, and were the seats of government and social intercourse between the members of the local governing classes. While government was conducted from the cities, production was conducted in the country. Consequently, the ideal of the Romans in administration was municipal, while their ideal in production was the system of house economy. The Roman accorded most prestige to citizenship and civil virtues, though his goods and wealth came chiefly from the country and were not made

in the city. Roman society was basically agricultural, but its ideals were municipal. The emperors tried to organize production according to the principles of house economy. Rostovtzeff states that Roman industrial organization never reached the scale of the Greek in the Hellenistic period.

The organization of production according to the principles of house economy was one of the influences which hindered industrial development in Roman society and prevented the accumulation of the soil from which science springs. Roman capitalists had two attractive investments only, in land and usury. They had little incentive to speculate and experiment and encourage new processes of production, which might have inspired improvements in mechanics and science. Local self-sufficiency, the backwardness of transport and the absence of a big market were interrelated, and inhibited initiative and invention. Rostovtzeff has attributed the failure of the Romans to develop big industry to absence of competition. This was due to the feeble demand, and the small number and buying capacity of customers in the type of society they had created. The more vigorous development of Hellenistic industry was due to the great export and carrying trade of the Greeks with the foreigners outside their realms. Trading conditions of this type did not exist in the Roman Empire after Augustus, because all the Mediterranean world was enclosed and organized in innumerable small local self-sufficing units. Though the scale of unification by law and government was progressive, the scale of industrial development was retrograde. The decline of Roman science in relation to Greek science is connected with these events.

The Platonic method of subjecting the masses by teaching them superstition was extended by the Roman Senate. The Greek historian Polybius observed it when in Rome in the second century B.C., and in admiring sentences ascribed the success of the Roman power to its skill in exploiting this technique.

Farrington has ascribed one of the causes of the decline of

Greek and Roman science to this encouragement of belief in lies and superstition for political ends. Plato, who advocated fictions for the people and the restriction of knowledge to the ruling classes, was compelled to attack Ionian natural philosophy. In Roman times, Cicero followed his lead. The Ionian attitude had been preserved by Lucretius, who had acquired it from Epicurus. Cicero strove to suppress the spread of Lucretius' views, and pretended to be ignorant of his works, though he knew them well and understood their merits.

The objectivity of the Ionian method made its users indifferent to social myths. Epicurus said that "the knowledge of natural law does not produce men given to idle boasting or prone to display the culture for which the many strive, but men of a haughty independence of mind who pride themselves on the goods proper to man, not to his circumstances."

His follower Lucretius wrote his great poem "On the Nature of Things," as a passionate protest against superstition. Farrington contends that the intensity of Lucretius' feeling, unsurpassed in literature, is a reflection of revolt against the increasing exploitation of superstition by the Roman Senate. He explains that Epicurus and Lucretius were philosophers in the Ionian tradition, and through the application of their objective analysis to the Greek and Roman social structure found themselves the exponents of democratic protest against oligarchic dictatorship, which was maintained by the deliberate manipulation of superstition. The suppression of Epicureanism, with its democratic connection, in the interests of the ruling classes led to the extinction of the Ionian method, of which it was the heir. The contemporary and later blackening of the reputation of the Epicureans and the assertion that Lucretius was mentally unbalanced were inspired by the desire of the ruling classes to discredit philosophers who had been led towards democracy through their study of science. When the Greek and Roman followers of the Ionian scientists were defeated, science also was defeated, and its growth halted.

28

MEDICAL RESEARCH AND THE REPUTATION OF MANUAL WORK

Farrington has drawn attention to Vesalius' ascription of the decline of Greek science to the Graeco-Roman contempt for manual work. The founder of modern anatomy, who wrote with special authority on the condition of ancient anatomy, expressed his opinions with force. He contended that surgery, or manual operation, was the most important branch of medicine, and that this depended on anatomy, which consequently is "the chief branch of natural philosophy, since it comprises the natural history of man."

The Hippocratic practice of manual operation continued until the time of Galen in the second century after Christ. Galen persisted in arduous dissections even in extreme old age. According to Vesalius, it died out after the sack of Rome by the Goths, when Greek science was forgotten and Romans relapsed into the habits of their ancestors. Doctors "gradually declined the unpleasant duties of their profession, without however abating any of their claim to money or to honour. . . . Methods of cooking, and all the preparation of food for the sick, they left to nurses; compounding of drugs they left to the apothecaries; manual operations to barbers."

When the doctors began to leave the preparation of drugs to slaves, it passed out of the control of educated men, and was conducted without criticism. The use of magical preparations and false remedies returned.

The effect of the divorce of manual operation from theoretical training was disastrous to the science of anatomy. The

doctor stood over his patient like an architect over a building, and gave verbal directions to the operating slave. This habit prompted the doctor to take more pride in his verbal knowledge and less in the experimental facts of anatomy. He presently convinced himself that even the facts of anatomy, such as the details of the structure of bones, muscles, nerves, arteries, veins, etc., were unimportant.

Verbal knowledge became separated from manual knowledge. While the doctor lost an accurate and lively grasp of anatomy through his avoidance of personal operation, his slave acquired some rudimentary knowledge from manual experience but was unable to benefit much from it. He could not read the learned treatises which recorded existing knowledge, and was unable to relate what he had observed to what was known. He could not understand much of what he had seen, and could do little to preserve or advance the science. This procedure survived until the beginning of the Renaissance. Professors of anatomy seated themselves at a distance from the cadaver and verbally directed ignorant assistants to make the dissections. These were botched before the students' eyes, while the professor "contemptuously steered the ship out of the manual." Students could have learned more by watching a "butcher in his stall."

The virtually complete separation of theory and practice which occurred in medicine in Roman times reflects the general Roman tendency to learn earlier science by rote, without learning the method by which it was discovered. One of the most remarkable results of this habit is seen in the history of anatomy. The successors of Galen taught anatomy for twelve hundred years before any of them discovered that the dissections he described were not of human bodies but of monkeys.

The governing classes were accustomed to issue orders on the basis of theoretical knowledge. Statesmen and generals were the ideal examples of this type. Doctors attempted to qualify for the same status by reducing medicine to an issue

of orders. They tried to emulate architects, who supervised building operations but did not use their own hands, and thus qualified, with reservations, as gentlemen.

The Romans were developing a tendency exhibited long before by their Greek predecessors. Plato divided science into two sorts: theoretical and practical. He gave the theory of numbers as an example of theoretical science, and carpentry as an example of practical science. He was of the opinion that gentlemen might take an interest in pure but not in practical science; in the theory of numbers but not in carpentry. He regarded architecture as a pure science with a direct relation to practice. This made the status of the architect uncertain, for though his science was theoretical, because he had to supervise and direct, it was also closely related to practice, and this slightly infected his profession with disrepute.

Farrington has remarked that Plato uses the same Greek word in referring to the manual operations in surgery and in carpentry. Surgery was therefore in danger of being even more disreputable than architecture, so doctors naturally became anxious to remove all manual elements from their science.

The social system of slavery tended to discredit manual work and to separate theory from practice. The advance of science since the Renaissance has been marked by the return to a balanced combination of theory and practice. Vesalius was aware that his own discoveries were due to his combination of theoretical study with intense practical work on dissection, and he announced that this was the correct method of discovery, and called on the young to advance science by its aid.

29

REFLECTION OF ROMAN CONDITIONS IN ROMAN SCIENCE

The Roman interest in country life stimulated the observation of plants and animals. This is reflected in the writings of Virgil, and the compilations of nature study by Pliny, who believed that nature was for the service of man, and also in the realistic representation of plants and animals in Roman art. If contrary influences had not existed, this development of observation shown by realism would have been beneficial for science. The Greeks made no realistic representations of plants. Their idealization in art is related to geometry rather than observation, and its defect as an ally of science is the same as that of geometry. It is too theoretical.

Singer has remarked that the non-scientific attitude of the Romans was related to their rhetoric and stoicism. This perhaps may be explained by the prestige of words in a society in which the governing and productive classes were sharply separated. In a democracy oratory, or realistic discussion, is essential. Under dictatorship oratory is transformed into rhetoric and becomes an idealized mode of expression in order to avoid offending the ruling power. Roman rhetoric, unlike Roman nature study, was idealistic. This was owing to its association with the city, and the expression of a governing class not personally engaged in production, and therefore not interested in material observation. It was the natural mode for the description of Roman grandeur, which was concerned with administrative rather than productive values.

While the Roman agricultural interest inspired nature study,

the municipal interest inspired drainage and sanitation. Rome had subterranean sewers in the sixth century B.C. The citizens gave much attention to the drainage of marshes to prevent the spread of malaria. They adopted the system of water supply by aqueducts, and in the course of centuries constructed fourteen, which ultimately provided a daily water supply of three hundred million gallons. No modern city is better supplied.

The greatest Roman contribution to medicine was the hospital system. This, again, was a product of organization rather than invention. The Romans organized hospitals at suitable centres in the Empire, especially for the service of the army. These later provided the pattern for the medieval hospitals. The status of physicians rose steadily. In 450 B.C. they were slaves, but four centuries later Julius Caesar had conferred citizenship on all physicians practising in Rome.

The enormous architectural constructions of the Romans demanded considerable engineering knowledge, but there is little evidence of any important advance on that of the Greeks. Roman architectural technique has been described by Vitruvius, who wrote in the first century B.C. His descriptions of buildings and machines are notably realistic, but his occasional expressions of opinion on theoretical science show traces of mysticism. He advocates the design of ornaments by "imitations of reality," and he writes in a style free from literary mannerism, which is intended to present his matter in the most effective way to works managers and skilled artisans. His book has recently been retranslated by Granger, who compares his writing with that of Michelangelo, who wrote in a rough direct style, and of Leonardo da Vinci, who was notably inept in languages. Leonardo did not even learn Latin until late in life, and he uses the written language of a Florentine shopkeeper of the lower class.

The connection between social status, literary style, and freedom from mysticism in workers such as Vitruvius and

Leonardo is significant for the explanation of the development of science.

Galen practised in Rome, but was the son of a wealthy Greek architect. He boasted that his competitors wept because they had not been able to obtain such a good education owing to poverty, and had less genius. He scorned those who spent the morning visiting their friends, and the evening in dining out with the rich and powerful. Thorndike remarks that he complained that the rich men could see the use of arithmetic and geometry, which assisted them to keep their accounts straight and build comfortable houses, and of divination and astrology, by which they sought to learn who would die and whose fortunes they might inherit, but they had no appreciation for pure philosophy though they admired rhetorical sophistry.

Galen did not consider that utility is the proper motive for encouraging science. He did not justify his researches in physiology by their utility, or even as contributions to pure knowledge. He asserted that the study of the parts of the body revealed a divine design, and provided the data for "a truly scientific theology which is much greater and more precious than all medicine."

He admired astrology, and opposed the atomists because "they despise augury, dreams, portents, and all astrology," and deny the existence of a divine artificer and an innate moral law. He regarded atheism and disbelief in astrology as comparably disreputable.

The repute of astrology was due to primitive belief in magic, and was strengthened among educated men by the Stoic philosophy. Stoicism had been founded in Athens in the third century B.C. According to its tenets, all things, including the soul, were material, and interconnected by forces. These forces were a refined species of the concepts of action at a distance, evolved by magicians in prehistoric times. The good life consisted of a proper adjustment of the process of living to nature, made by controlling the interconnecting forces through reason.

The theory of the macrocosm and the microcosm was consonant with this view. Features of the larger universe, such as the stars, were connected by forces with features in the microcosm, or human body. For instance, the constellation of Leo is connected with the heart, and Pisces with the feet. Life could not be adjusted to nature without a knowledge of nature and astrology, so Stoicism encouraged nature study and astrology. The theory of the macrocosm and microcosm is not purely speculative. The dependence of all life on the sun and the lunar periodicities in women's lives are positive evidence of some connection between man and the stars. Given these facts, elaboration of connections by speculation seemed plausible to minds which had not thoroughly assimilated the technique of experimental proof. Even so great a scientist as Ptolemy, whose studies of the refraction of light by air and other media are perhaps the most brilliant contribution to experimental physics made in antiquity, and whose astronomical and geographical works were authoritative for nearly one and a half millennia, was an ardent astrologer. In his treatise on astrology, the *Tetrabiblos*, he describes how the influence of the planets and stars on the body and mind, and on disease, may be calculated. The sun warms and drys, the moon cools and putrefies, Saturn chills and Mars emits a parching heat. Jupiter is lukewarm, Venus moist, and Mercury changeable. The fixed stars exert their influence in conjunction with planets.

The spread of Stoicism had important effects. Its assertion of the interrelatedness of all phenomena contradicted the beliefs of polytheism, and prepared the path to the belief of those who, with Pliny, asserted that "Deity only means nature." Virgil was a monotheist and regarded the world as a work of art made by God. The uneducated Romans remained with the belief that the various phenomena of the world were governed by a multitude of gods. Stoicism produced a profound division in religious views between the governing class and the lower classes. The latter retained the orthodox faith taught by the

priests, while the former were sceptical of it. This class division in belief damaged the solidarity of Roman society, and contributed to its decay.

The Stoic view that all the phenomena of the world are interconnected implied that the events of human life are determined, and their course may be forecast. Astrology was the technique by which this could be done.

The Christians were opposed to Stoicism because of their belief in free will. Their opposition to determinism led them to attack astrology. But this was not because it was based on unconfirmed speculation. When Galen wishes to give an example of this, he refers to the Christians. Someone had been unduly speculative in his presence, and he said he felt "as if one had come to a school of Moses and Christ and had heard undemonstrated laws."

Thorndike remarks that the Christian writers of the Roman period regarded all things as contemptible compared with divine revelation, but apart from that, they had more respect for Greek philosophy and science than any other system of ideas. He comments on the views of Basil, who lived in the fourth century. "At all events," said Basil, "let us prefer the simplicity of faith to the demonstrations of reason." After this expression, he quotes good Greek science with sympathy for the illustration of his sermons. He often gave the best current theories of natural processes to hold the interest of his audiences. He spoke of God as the supreme artisan and made flattering allusions to the value of techniques which support life or produce enduring work, such as the construction of waterways and the development of sea trade. These technical references suggest that Basil's audiences included many artisans, and that Christianity was spreading among manual workers who were oppressed by bad conditions and desired a better world.

Augustine was less sympathetic than Basil to science. He was the son of a man of wealth and rank, and inclined to think in

the psychological mode of a member of the governing class, interested in ideas rather than things. He condemned "the vain and curious desire of investigation" through the senses, which is "palliated under the name of knowledge and science." He allowed that astronomy was useful for determining Easter, but not for interpreting the Scriptures. Though he did not rebut the fundamental hypothesis of astrology, he was deeply opposed to it, because he could not combine it with his theory of free will and predestination.

The disintegration of Roman society and its culture was accompanied by the almost complete cessation of effective scientific research, but magic, astrology and the occult sciences did not decline. They may have increased, but this is not easily decided. There was a thick undergrowth of occult science through the best period of Greek civilization, and when the brilliant flowers of science faded, the presence of the undergrowth, always there, became more prominent. The overwhelming proportion of occult science to true science, especially in the period from the founding of the Roman Empire until the Renaissance, is demonstrated in the pages of Thorndike's treatise on the history of magic and experimental science. The almost universal failure of even the greatest minds to perceive the elementary fallacies in occult science is frightening.

The basis of occult science is intense human emotion. If a person desires or fears something, he unconsciously observes and criticizes it incorrectly. If he desires the death of a powerful enemy, he will try to secure it by striking an image within his reach. He tries to achieve his end by false analogy, and persuades himself that an imitation of the desired action is as effective as the action itself. He may affect an object at a distance not by performing a motion analogous to one which would do harm, but by a special act. He may hope to make an enemy ill by sticking pins in a wax image, or by making a pass with his hands. The motions made in hunting, warfare,

and in all branches of technology were known to be effective in their particular spheres. The belief developed that these motions of skill had an effectiveness, even when separated from their object. For instance, the blacksmith's particular way of swinging a hammer would seem to acquire a potency in itself. All of the skilful acts of the technicians became magical acts. From this it was deduced that skilled motions might in themselves possess a potency, and that their performance might influence persons and objects at a distance.

Technology and magic were interwoven, and each motion made in early technical processes was accompanied by incantations, and other signs of the magical power of the skilful act.

The effect of many herbs on the body and mind was real. This encouraged exaggeration of the potency of plants, and beliefs in the magical properties of objects. The belief was acquired that certain stones had life-giving power, and could communicate fertility and strength through touch. Precious stones were deemed extremely potent, and superior to herbs because more durable. The search for minerals with magic potency inspired much alchemical research, and incidentally provided some new knowledge of true chemical processes, and some new materials of real value. The belief in the potency of objects could become so intense that some persons died by mental shock through touching them.

The belief that the future could be forecast by astrology inspired keen interest in astronomical observation, which incidentally provided data for genuine science.

The enormous practice of magic during the Graeco-Roman and Middle Ages did produce some positive contributions to science, but the result was very small compared with the effort. Magic may be an important source of science in barbarous societies, but the example of these ages demonstrates that in civilized societies it is not.

The nature of the source in scientific development in highly differentiated societies is suggested by the change in the con-

ception of education which occurred between the height and the end of Graeco-Roman civilization. Varro, the friend of Julius Caesar, who was born in the second century B.C., defined a liberal education as a training in nine subjects. These were grammar, dialectic, rhetoric, geometry, arithmetic, astronomy, music, medicine and architecture. Cassiodorus, who lived in the sixth century after Christ, had reduced the number to seven by omitting medicine and architecture (which at that time included mechanics).

The particular decline in status of these sciences at a time when science as a whole declined suggests that they contain a combination of qualities exceptionally important for the development of science. The combination of theory and manual practice is evenly balanced in these sciences, so one may deduce that the development of science depends in an exceptional degree on an even balance of theory and practice. Singer has commented on the misfortune that Boethius, the author of the *Consolation of Philosophy*, who was a contemporary of Cassiodorus, omitted the observational and practical parts in his translations of the scientific works of Theophrastus and Aristotle. The decline of medicine, architecture and observational science in the time of Cassiodorus and Boethius was due to an increasing disrepute of the manual part of these sciences. Galen made his own dissections, but his successors relegated theirs to slaves and servants. When the manual part of science is not esteemed, experimental science is stunted, and science as a whole develops slowly, or with a theoretical lopsidedness which, like that of so much of Greek science, is mainly sterile in its own day.

30

THE REPUTE OF LABOR BEGINS TO RISE

The decline of science shown in the works of Boethius and Cassiodorus was related to the general decay of Graeco-Roman civilization. The internal weaknesses of the Empire were due chiefly to the failure to create a society that could improve and provide inspiration, and this could not be done without developing machinery and abolishing slavery. There are very few traces of hope in Roman authors. One of these occurs at the end of Seneca's treatise on physics. He discourses on the possibility of knowledge and writes: "How many discoveries are reserved for the ages to come when our memory shall be no more, for this world of ours contains matter for investigation for all generations." This zest for research was rare, and in the circumstances sterile.

The most famous movement against the bad conditions and pessimism of classical civilization was Christianity. This was started by a manual worker who was probably a master carpenter by craft. His social philosophy of respect for the individual and the poor implied an assertion of the rights of manual workers, and the need for an improvement of their condition. The widespread awareness of social disease disposed some conscientious men in all classes to adopt the new creed. When the needs which had inspired the creed presently created a powerful new institution this, as always in history, was captured by an astute leader and converted into an instrument of the governing classes. Constantine the Great, who reigned at the beginning of the fourth century, was the agent who incorporated the Christian Church into the apparatus of gov-

ernment. He bestowed on it enormous estates, and made its material interests similar to those of wealthy landowners.

The administration of the Church acquired the features of Roman imperial government, and preserved them after the disappearance of the Empire.

As the Empire weakened it became unable to resist barbarian invasions. The first serious one was due to the flight of the Germans in the valley of the Danube before the invading Huns in A.D. 372. The Roman outposts on the Danube were amazed by the spectacle of a whole nation floating on rafts up the river, in terror of the invaders. These barbarians were allowed to settle within the Empire and their status was established by appointing their king a general in the imperial army. Like other Germanic tribes, they were assimilated. They adopted Roman forms of government and Christianity. When they revolted, their kings respected Christian privileges and property. They were not hostile to Roman law and the Christian religion, though they barbarized them. The Romanized Church could survive under these conditions, and when the civil administration had disintegrated, the Church could continue to rule by its Roman principles. As Pirenne explains, the Church succeeded in acquiring and maintaining its control over society for centuries, not because it was Christian but because it was Roman.

The more extreme mystical forms of Christianity had led to solitary asceticism at an early date. A movement for organizing these solitaries in groups began about A.D. 348. Benedict founded in A.D. 543 the first organization of monks in Europe. The habits of the solitary ascetics were often unattractive, and apparently an excuse for mere laziness. When their numbers were small, these eccentricities could be tolerated, but when they were numerous they became a scandal to religion. The improvement of the respectability of their lives was one of Benedict's motives. He laid down rules of conduct for them, and ordered them to withdraw from secular life, which made

training and discipline easier. Benedict required his followers to honour God by labour, either manual or intellectual, besides prayer. This rule was an unconscious expression of the improving social status of manual labour. But it was not yet easily imposed, as slavery still existed. In some degree, it was a sublimation of slavery. The rule of seclusion assisted the establishment of the rule of work, as the monks could labour in the privacy of the monastery without losing prestige. Later, when the monastic movement had grown stronger, the respectability of manual work could be more openly expressed. The Benedictine rule of work helped to prepare the attitude towards manual work which later made the rise of modern experimental science possible.

Benedict's achievements deeply interested Gregory the Great, who became Pope in A.D. 590. Gregory brought the new monasteries under the central control of the Church. Owing to the rules of work and study, the monastic estates were profitable, and their owners were relatively literate. The Pope had a large new source of income, and a system of relatively competent administrative offices throughout the Empire. He used his new resources for the extension of the power of the Church. He carefully organized and achieved the conversion of Britain to Christianity. The new educated monks were sent to Britain to learn the language and customs of the natives, and he could afford to keep them there for a long preliminary period until they had mastered their task. Consequently, the British were tactfully converted with the minimum of trouble, and remained exceptionally loyal members of the Church for many centuries. While a new theological civilization was growing out of the European ruins of the Roman Empire, a social explosion occurred in the Imperial ruins of the Near East.

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31

THE MATERIAL AND TECHNICAL BASES OF ISLAM

Arabia is not fertile or rich in resources, and was never thoroughly colonized by the Romans and Byzantines because it did not promise much profit. Its population in the sixth century after Christ consisted largely of barbarous tribes organized on the clan system, with polytheistic religious beliefs. The economic condition of southern Arabia had been declining for centuries. This may have been due to increasing desiccation or to political disintegration. It was reflected in the decay of the public waterworks upon which the prosperity of the country depended. Owing to these circumstances, Arabs were migrating towards the north and east, and for a long time had produced unrest on the frontiers of Syria and Persia. Signs of reaction in the Semitic countries against Hellenistic civilization had appeared in the third century after Christ. Intense hatred of Byzantine and Persian rule had accumulated in the frontier populations of Syria, Egypt and Persia in the sixth century. The oppression which created this hatred had been employed to squeeze tribute for the support of inefficient governments poor in military spirit.

The old tribal religions had sanctuaries in various places. One of the most revered was at Mecca, and consisted of a rectangular hut known as the Caaba or Cube, containing the image of a tribal god. This sanctuary had long been the object of pilgrimages from the surrounding country.

Religious changes were occurring. Sects such as the Hanifs had begun to advocate the supersession of the traditional poly-

theism by monotheism. Mahomet was born at Mecca in this social and religious environment in A.D. 570. He was employed at the age of twenty-four by a rich woman older than himself, who had been twice married, to undertake a commercial expedition to Syria. He performed this successfully, and became the third husband of his employer. He prospered in trade for some years, and had several children. Then he discovered in himself reforming and prophetic inspiration. He became a fervent monotheist, and acquired vague conceptions of Christianity, possibly from Syrian Christians during his travels. He began fasting and solitary vigils, and had hysterical paroxysms like violent fever, and believed that these were signs of divine inspiration.

He identified Allah with the god of the Jews by instructing his followers to turn towards Jerusalem to pray. Later he ordered them to turn towards Mecca. The act of surrender to the new faith was named Islam, and those who surrendered themselves, Muslims. Most of his early converts were of the lower classes, or slaves. They became unpopular in Mecca, but Mahomet survived through the protection of his tribal clan. The majority of the clan were unbelievers, but would not deliver him to his enemies owing to the tribal tie of blood. The other members of the tribe, though they were unbelievers, would have declared a blood feud if he had been assassinated.

The Meccans lived chiefly by commerce, and were poorer than the Judaized Arabs living in the fertile country to the north, around Medina. The Medinians were superior to their neighbours in mechanical arts and metal working. Power in this community was held by the Jews, but gradually passed to two tribes, who contended for supremacy. Mahomet was invited to Medina to preach his monotheistic religion, and to mediate in this tribal struggle. He established himself and his followers in Medina by exploiting the political situation, and after this emigration from Mecca he ordered his followers to

turn towards the sanctuary during prayer. His injunctions improved the position of women and slaves and he severely condemned fornication.

The Muslims suffered great economic hardships in Medina, and tried to relieve their position by pillage, even in the four months when tradition did not permit raids. Mahomet gained his first military triumph in A.D. 623. With three hundred men he successfully attacked a rich Meccan caravan, protected by nine hundred soldiers. He out-manoeuvred his opponents by occupying the only well on the field of battle, and exposing them to thirst besides military action. He did not take part in the fighting, but prayed continually, with violent trembling. His victory was received as a miracle, and on his return to Medina he assassinated his opponents, and expelled the Jews and confiscated their property.

Mahomet broke from Arabian military tradition in later campaigns, and used fortifications, which were dreaded by other Arabs, and regarded as dishonourable. The vigilance and discipline of his followers gave him advantages over the superior numbers of his Arabian enemies. His Jewish opponents refused to resist him by arms, though they died rather than accept his religion.

Mahomet had become the master of a large part of Arabia. The ancient pagan pilgrimages to Mecca continued, but Islam was imposed on them. They remained the social mechanism which held the Muslims together. The numerous problems of government and social organization began to press heavily on Mahomet. One serious difficulty was presented by the vagaries of the calendar. The Arabs had measured the year by the sun, but the months by the moon. As these do not fit exactly, they occasionally introduced an extra month when the calendar had become uncomfortably out of step with the seasons. Mahomet attempted to abolish the confusion by announcing in the name of Allah that in future the year would contain exactly twelve lunar months. This made the confusion of the calendar in Is-

lam permanent. The later Muslims had to give keen attention to this problem of the calendar to combine sacred with practical needs, as the religion could not be truly conducted by the faithful without an accurate lunar calendar, and their agriculture and trade could not be carried out without an accurate solar calendar.

This confusion in the measurement of time, due to Mahomet's calendrical decree, inspired the construction of astronomical observatories, whose astronomers incidentally made important contributions to science.

Mahomet died in 632, after he had firmly established his reformed state and religion. The number of his followers was quite small, but they had good generals and fresh inspiration and discipline. They became the leaders of all the Arabian tribes struggling at the frontiers against the Byzantines and Persians. They were invited by the oppressed Semites in Syria to deliver them, and in A.D. 634 they captured Palestine. They occupied Egypt with similar help from the subject population, and swept along the coast of Africa. They crossed the Straits of Gibraltar in A.D. 711. The armies in the East conquered Persia and Mesopotamia. Within eighty years Islam had created a tremendous empire. The chief source of its success was the rottenness of Graeco-Roman society. In the southern and eastern Mediterranean it collapsed under the attack of a small but determined force. Another source of success was an important innovation in military technique. The later Arabian armies had superior cavalry, which achieved most of their military victories. The early Muslims did not have many horses and were not very skilful with them, but they learned the technique of military horsemanship from the Persians, who in turn had learned it from the Chinese.

The efficient stiff curved saddle had been invented by the Chinese in 200 B.C. They invented the stirrup about A.D. 600. These technical inventions were the source of the military efficiency of the Mongolian nomads. They could fight securely

from their saddles, and after the invention of stirrups could shoot effectively with bow and arrow while riding at full gallop. This skill was supported by the severe training of the nomads' life, which accustomed them to long rides and swift action, with the minimum of food.

The Arabs learned these techniques from the Chinese through the Persians, and used them against bewildered foot-soldiers in the West. They were not anxious to convert conquered peoples to Islam. They wished to put them under tribute, and could not do this if they became Muslims, as members of the faith could not be taxed. This policy had two effects. It created considerable religious toleration and concentrations of wealth at government centres. Part of this wealth was spent on the construction of palaces and the encouragement of culture. It provided the financial support for the brilliant scientific activity of Islam.

32

THE MUSLIMS CONQUER SCIENCE

The Islamic Empire spread to Spain and India. The Arabs were a minority in its population, and formed a relatively small governing class. Their first headquarters had been at Medina, and were transferred to Damascus in 661. The capital was moved again to a more central position, when the Caliph al-Mansur founded Baghdad in 762. Before this date the Muslims had been continuously active in conquest, and had not produced any literature. They now became more administrative, and began to cultivate the techniques of urban and sedentary life. Al-Mansur engaged engineers, astronomers and scholars to plan, build and manage his new city. These included many foreigners such as the Jew Masha'allah, and the Persian astronomer Naubakht. Masha'allah wrote the oldest book on science which has survived in Arabic. Like so many of the primary books in the history of science, it deals with a practical subject, the calculation of prices.

As Baghdad was built on the Tigris it was in direct communication by ship with India and China, and rapidly grew into a great trading centre. Aid in the calculation of prices was welcome. Indian knowledge followed Indian trade. The Indian astronomer Manka was presented at Baghdad by al-Fazari as early as 770. He brought with him the *Sindkind*, or Hindu treatise on astronomy, which was translated into Arabic. Al-Fazari constructed the first Muslim astrolabe and he prepared astronomical tables according to the Muslim calendar. Astronomy was immediately employed to determine the correct dates for Muslim observances, such as Ramadan. This fast occurs in the ninth month of the Muslim lunar year and is not

correlated with the solar season, so its limits could not be forecast without astronomical knowledge.

When the Arabs relinquished their nomadic life and settled in the cities they were attacked by diseases from which they had been free in the desert. The doctors familiar with urban diseases were Jews and Greeks, and were invited to practise at the Arab courts. The Arabs noted that their works of reference were in Greek, so they began to translate them. Batrik translated Greek medical works into Arabic soon after the founding of Baghdad, and also Ptolemy's treatise on astrology. This introduction to Greek astrology was an incentive to the study of astronomy. The foreign scholars were far more learned than the Arab governors, and the education of the young tended to be entrusted to them. The demands of construction, commerce, health and education stimulated interest in foreign learning.

Haroun al-Raschid ordered the translation of Hippocrates, Aristotle and Galen about the year 800, and his successor al-Mamun established a college for the translation of foreign works, and sent embassies to Constantinople and India to obtain copies of the most important. The college had a large staff of Syrian translators, who were named the caliph's doctors to protect them from attacks by religious fanatics. Yusuf translated the first six books of Euclid, and the *Almagest*, and editions of Apollonius and Archimedes were also prepared. This activity was followed by original research. Al-Mamun had a degree of the meridian measured by a new method. Observers starting from a given point were ordered to walk to the north and the south until they had seen the pole star rise or sink one degree. The distances they had traversed were measured, and their mean taken. Simultaneous observations were made at observatories in Baghdad and Jundeshapur, and used for the preparation of the *Tested Tables* of al-Mamun, and al-Farghani made a compendium of astronomy which was used by Regiomontanus at the beginning of the European Renaissance.

The cultural development at Baghdad was very rapid. Within a few decades the greatest Arabian mathematician appeared. This was Mohammed ibn Musa Abu al-Khwarizimi, the librarian of al-Mamun. He accompanied a mission to Afghanistan and may have returned through India. After his journey, about the year 830, he wrote the famous work *Al-Gebr We'l Mukabala*, which gave the name to the science of algebra, and was the medium by which the Indian numerals and decimal system were transmitted into Europe.

Al-Khwarizimi's work was based on that of the Indian mathematician Brahmagupta, who lived in 660. Brahmagupta wrote a treatise in verse on astronomy, arithmetic and algebra. His arithmetic was largely devoted to the calculation of rates of interest. He worked out the fundamental propositions concerning arithmetical progressions, and solved a quadratic equation. He solved several indeterminate equations of the first degree, and one of the second degree: $nx^2 + 1 = y^2$. Fermat sent this problem to Wallis and Brouncker as a challenge one thousand years later, and Brouncker found the same solutions as Brahmagupta.

Al-Khwarizimi may have learned of Brahmagupta's treatise from Hindu scholars in Baghdad, or during his Indian travels. He may have learned the Indian numeral system from the Hindu tables brought by Manka, or from Arab merchants. Hindu merchants began to use these numerals about the year 700. Arab commerce with India was growing rapidly then, and the Arab merchants probably adopted them at once. The Hindus and Arabs did not use the abacus, so a convenient numeral system was of great assistance in trade.

Al-Khwarizimi gave rules for the solution of quadratic equations, which he classified in five types. He described the unknown quantity as the root (like the hidden root of a plant). He surpassed the Greeks in recognizing that a quadratic equation has two roots. He was familiar with the methods of Euclid and gave geometrical besides alegbraical solutions.

Al-Khwarizimi writes in his preface that al-Mamun "has encouraged me to compose a short work on Calculating by Completion and Reduction, confining it to what is easiest and most useful in arithmetic, such as men constantly require in cases of inheritance, legacies, partition, lawsuits, and trade, and in all their dealings with one another, or where the measuring of lands, the digging of canals, geometrical computation, and other objects of various sorts are concerned. . . ."

Gebr is the operation of completing the form of an expression; for instance, an expression may be converted into a perfect square by completing it through the addition of a number. *Gebr* was used to signify the restoration of something broken, especially bones; the Spanish and Portuguese describe a bone-setter as *algebrista. Mukabala,* or reduction, comprises the subtraction of equal quantities from both sides of an equation, to reduce it to a convenient form. Al-Khwarizimi starts with the statement: "When I considered what people generally want in calculating, I found that it always is a number."

The first third of the work consists of solutions of quadratic equations, without reference to applications. For instance, "A square and twenty-one in numbers are equal to ten roots of the same square," i. e., $x^2 + 21 = 10x$. His solution is: "Halve the number of the roots; the moiety is five. Subtract from this the twenty-one which are connected with the square; the remainder is four. Extract its root; it is two. Subtract this from the moiety of the roots, which is five; the remainder is three. This is the root of the square which you required, and the square is nine. Or you may add the root to the moiety of the roots; the number is seven; this is the root of the square you sought for, and the square itself is forty-nine."

More than half of the remaining part deals with the division of legacies, with other short sections on mercantile transactions, mensuration, capital and money lent. Seven species of legacy are discussed. This is an example: "A man dies, leaving his mother, his wife, and two brothers and two sisters by the

same father and mother with himself; and he bequeaths to a stranger one-ninth of his capital."

As a widow was entitled to one-eighth, and a mother to one-sixth of the residue, thirty-four forty-eighths remained to be distributed between the two brothers and two sisters.

About one-quarter of the book deals with calculations of inheritances in which the law of inheritance, which leads to the estimation of the quantities handled in the calculations, is interpreted to favour heirs and next of kin, and limit the power of testators to bequeath property or emancipate slaves during illness. The effect of the emancipation of a slave during the illness of the testator is calculated in the solution of the problem: "Suppose that a man on his sick-bed makes to another a present of a slave-girl worth three hundred dirhems, her dowry being one hundred dirhems; the donee cohabits with her, and afterwards, being also on his sick-bed, makes a present of her to the donor, and the latter cohabits with her. How much does he acquire by her, and how much is deducted?" The solution shows that the legacy of the donor to the donee should be one hundred and two dirhems, while the legacy of the donee to the donor is twenty-one.

Al-Khwarizimi ends his treatise with the words: "God is the Most Wise!"

Indian and Arabian algebraists give a great deal of information about the social and economic conditions of their times. The Indian Bhaskara, who flourished after al-Khwarizimi in the twelfth century, discusses calculations on the value of slaves, and mentions that the price of a female slave is at a maximum at the age of sixteen years, and decreases in inverse proportion to the age. At sixteen she was worth about eight oxen who had worked for two years. The prices of food and labour are given, and one learns that the rate of interest on money was three and a half to five per cent per month.

Indian and Arabian mathematics was founded in economic need. The Arabs were traders and lawyers with a positive and

practical outlook. They expected calculation to serve commerce, and astronomy to guide the caravans across the desert, or to tell the hours of prayer or the moment of the appearance of the moon of Ramadan. Carra de Vaux remarks that the Arabic language is dry and precise, and recalls the style of Voltaire. It is more suitable for scientific exposition than for poetic composition, or the expression of reverie. New technical terms may easily be coined in it. The Arabs did not write in verse, and had little taste for problems of infinity. The writers in Arabic were devoted to exposition rather than original thought. Their books were well arranged, lucid, and impersonal, like good textbooks. They did not address their arguments to individuals, in the manner of the ancient Greeks, and this absence of individual feeling is probably connected with the precedence of exposition over originality in their works, and also with the structure of the social system.

All persons living under an absolute government are servants, and expect to receive and give orders. They do not expect to be persuaded by appeals to their individual reason. In such a society, authors and students approach learning with this attitude. The author is the authority, and instructs the mass of impersonalized students who merely learn, and feel no duty to question what they are taught. This attitude inhibits original research.

The geometer Thabit, who was born in 836, wrote commentaries on most of the great Greek works on mathematics. He translated Apollonius, and discussed the postulates of Euclid. He wrote the earliest known treatise on the sun-dial, which is probably an Arabic invention, and registers the hours by equal measures at all seasons.

Thabit's achievements were succeeded in 877 and the following decades by those of al-Battani. He compiled extensive astronomical tables, popularized the use of the sine, tangent and cotangent, and gave the fundamental formula in spherical

trigonometry which expresses the side of a triangle in terms of the other sides and their included angle.

Abul-Wafa used the trigonometrical formula for the expansion of the sine of the sum of two angles before 980, and compiled a table of sines and tangents for every ten seconds of arc. In the same period Farabi wrote a treatise on music. He was aware that the addition of intervals corresponds to the multiplication of the chords which define them, and therefore possessed a clue to the conception of logarithms.

The first Muslim university was founded at Baghdad in 1065. Omar Khayyám was one of its greatest teachers. He classified cubic equations into twenty-seven types, and showed how they could be solved geometrically from the intersection of a conic and a circle. A similar method was rediscovered by Descartes five hundred years later. Khayyám solved one biquadratic equation, and is said to have stated the first example of Fermat's theorem, that the sum of two cubes cannot be expressed as a cube. He was a follower of the liberal theologians, whom al-Mamun himself had supported, and believed with them that the Koran was created in time and had not existed from eternity, and that theology must submit to intellectual criticism.

The universality of the Arabic language in the Islamic Empire assisted the rapid transit of knowledge from one end to the other. The culture of Baghdad diffused swiftly to the Muslims in Spain. Al-Zarkali, who died in Spain in 1087, wrote an important treatise on the astrolabe, and other Moorish astronomers compiled tables based on the meridian of Toledo, which remained for a long period the chief meridian of reference in Europe.

The Arabian achievements in calculation, algebra and astronomical observation have Babylonian characteristics. The remnants of Babylonian civilization lay within the Islamic Empire, and their impress was not entirely lost.

33

THE MUSLIMS EXTEND ALCHEMY

The Muslims followed their predecessors in the study of alchemy with particular distinction. They learned the science chiefly from the works of the Alexandrian alchemists, such as Zosimos and Mary the Jewess, which have been mentioned in an earlier chapter. It is said that Prince Khalid summoned the Christian alchemist Marianus from Alexandria to Damascus at the end of the seventh century, to expound the science. They acquired something from the Hellenized scholars at centres such as the Academy of Jundishapur in Persia, and Harran in Mesopotamia, which survived in Islamic times. Harran had been occupied by Alexander the Great, and its inhabitants retained traditions of Greek and Babylonian science.

The greatest Arabian alchemist was Jabir ibn Hayyan, or Geber. He was born in 721 and became eminent at Haroun al-Rashid's court at Baghdad. Jabir inspired the second importation of Greek scientific books from Constantinople. He studied nearly all of the newly revealed knowledge, but gave particular attention to alchemy. As has been explained in an earlier chapter, the Alexandrians combined much magical and mystical speculation with their experiments, and Jabir naturally began by acquiring the same conceptions. But when he continued with original work, he gave more weight to experiment and less to speculation. Aristotle had conceived metals as a combination of watery and earthy exhalations in which the former predominated, and his theory had been accepted for a thousand years. Jabir had the courage to propose a more definite theory. He asserted that the two exhalations did not immediately form metals when imprisoned in the earth, but passed

through an intermediate stage, in which the earthy exhalation was converted into sulphur and the watery into mercury. The metals were then formed from the combination of these two substances. If the constituents were absolutely pure, they formed gold, and if less pure, silver, copper, etc., in descending degree. The common metals might therefore be transmuted into gold if the impurities could be removed, and alchemy was the technique by which this might be done. Jabir attempted to prepare metals from the combination of sulphur and mercury, and obtained cinnabar. He concluded that the two principles of which metals are supposed to be formed are not ordinary sulphur and mercury, but hypothetical substances which resembled them.

He was acquainted with crystallization, calcination, solution, sublimation, etc., and attempted to explain their nature. He described methods of preparing steel and other metals; dyes for cloth, leather, and hair; varnishes for water-proofing cloth and protecting iron; and substitutes for inks containing gold. He knew the use of manganese dioxide in glassmaking. He was familiar with citric acid and knew how to concentrate acetic acid by distillation of vinegar, and he discovered nitric acid.

The magnitude of his intellectual achievement in science is reflected in his consciousness of the place of experimental research in chemistry. He expresses this in a passage which is perhaps the most distinguished in Arabian science. He says: "The first essential in chemistry is that thou shouldest perform practical work and conduct experiments, for he who performs not practical work nor makes experiments will never attain to the least degree of mastery. But thou, O my son, do thou experiment so that thou mayest acquire knowledge. Scientists delight not in abundance of material; they rejoice only in the excellence of their experimental methods."

Jabir was followed by Razi, who was born in 866. He was not quite so original, but he was far more systematic. He was the first chemist whose writings were almost entirely free from

mysticism. He gave comprehensive lists of the instruments used in melting metals and in general manipulations. The first included the blacksmith's hearth, bellows, crucibles, descensories, ladles, tongs, shears, pestles, files and iron moulds. The second included beakers, glass cups, iron pans, sieves, heating lamps, flasks, phials, jars, cauldrons, sand-baths, water-baths, ovens, hair cloths, linen filters, stoves, kilns, mortars, glass funnels and dishes.

He gave the first systematic classification of experimentally defined chemical substances. These were arranged under the four headings of mineral, vegetable, animal, and derivative. The mineral substances were sub-classified under the headings: spirits (such as mercury, sal-ammoniac and sulphur); bodies (such as the metals); stones (such as pyrites, metalliferous ores, mica and glass); vitriols (such as iron and copper sulphates); boraces (such as borax).; salts (such as sodium carbonate and slaked lime). The derivative substances included litharge, red lead, cinnabar, caustic soda and various alloys.

This scheme exhibits a remarkable range of chemical knowledge and much insight into the chemical relationships between the chief sorts of matter. More chemical facts and technical refinements were added to this scheme by the later Arabian alchemists. By the thirteenth century they had mastered cupellation, the separation of gold and silver by nitric acid, and the extraction of silver by amalgamation with mercury, and they could make quantitative chemical analyses of alloys of gold and silver. But no great advance on this achievement was made until the seventeenth century.

The experimental researches were directed by the theory of transmutation. This aimed at the conversion of base metals into gold, and was naturally combined with the search for elixirs which would restore the vitality of the declining body. It was inspired by the love of gold and life, and power over them. The equipment of the alchemist was virtually the same as that of the metallurgist and craftsman.

34

FURTHER MUSLIM SUCCESSES AND FAILURES IN SCIENCE

Razi's excellent work on chemistry was less famous than his comprehensive summary of Greek, Syriac and contemporary Arabian medicine. This was perhaps the longest work ever compiled by one man on medicine. It was a lucid account of the best medical knowledge. In addition to this summary, Razi wrote some original works on clinical and therapeutic medicine. He gave the first clear account of smallpox and measles and a description of suitable treatment for the smallpox pustules. Four centuries later, Ibn al-Khatib of Granada wrote an equally famous treatise on the plague, or Black Death of the fourteenth century. He described the transmission of plague by garments and persons and the arrival of infected ships in healthy ports, and commented on the immunity of isolated individuals and nomadic Bedouin tribes in Africa.

The Muslim physicians also made important contributions to pharmacology. The names for some of their preparations, such as julep and syrup, have passed into modern languages. Abu Mansur Muwaffak compiled about 975 a work which contains a description of five hundred and eighty-five drugs. He was the first to distinguish between sodium and potassium carbonates. He recommended quicklime as a depilatory, and was acquainted with arsenious oxide and silicic acid, or tabashir, obtained from bamboo, and antimony. He was familiar with the poisonous properties of copper and lead. He recommended a mixture of gypsum and white of egg for making plaster for bone-setting.

The Arabians collected information on many plants and drugs unknown to the Greeks. They introduced camphor from the Sunda islands, musk from Tibet and sugar-cane from India. These innovations arose directly from the extent of their empire and trade.

Their contributions to anatomy and physiology were small. This was connected with the Muslim prohibition of dissection of human and animal bodies, which prevented them from making physiological experiments and discovering the mistakes in Galen. They contributed virtually nothing to zoology, and little to botany. The prohibition of dissection, and also of the pictorial representation of living organisms, hindered the study of these sciences. Hogben has pointed out that the Arabian conquests, unlike those of the Europeans in later centuries, did not bring unknown fauna and flora to their notice, and were not particularly stimulating to students of natural history. The first Islamic tribes were desert peoples. They may have failed, like the inhabitants of modern industrial cities, to become deeply interested in natural history owing to the poor fauna and flora of their home. The early lack of interest became established as a tradition. The taste of the Arabs and modern citizens for geometrical art may be related to this common feature in their environments.

The construction of the new Muslim cities in Mesopotamia and elsewhere required high engineering skill. The Muslims prepared good works on the principles of mechanics and the methods of constructing irrigation canals and water conduits. They wrote books on water clocks, water wheels and balances. The water clock presented by Haroun al-Rashid to Charlemagne has become famous. But they did not advance mechanics beyond the stage in which it was left by Hero of Alexandria before A.D. 200.

The contributions to physics were also small, with one notable exception. This was made in optics by Alhazen, who was

born in 965. He criticized the theory of Euclid and Ptolemy on optics, and contended that "it is not a ray that leaves the eye and meets the object that gives rise to vision. Rather the form of the perceived object passes into the eye and is transmuted by its transparent body" (the lens of the eye). He established the law that incident and reflected rays lie in the same plane, and he investigated the properties of spherical and parabolic mirrors. He was the first to record the phenomenon of the camera obscura. He observed the semi-lunar shape of the image of the sun thrown on a wall in a closed room, by rays entering through a small hole in the window shutters. He studied the phenomena of twilight, and calculated that the sensible atmosphere must be about ten miles high. He very nearly discovered the theory of the magnifying glass, and had much insight into the nature of focussing, magnification, and inversion of the image, and the formation of rings and colours by optical experiment. He propounded the famous problem: "In a spherical or convex, a cyclindrical or conical mirror to find the point from which an object of given position will be reflected, to an eye of given position." It involves an equation of the fourth degree, which he solved with the assistance of a hyperbola.

Alhazen's optical work was the basis of that of Roger Bacon, and influenced Leonardo and Kepler. His profession was medicine, but he was the first to give an account of the human eye from the perspective of a physicist. Alhazen's remarkable achievement was inspired by medicine and astronomy. As further great contributions to physics were not inspired in Islam by these sciences, it is permissible to conclude that they are not sufficient incentives to the cultivation of physics. Some other important incentives must have been lacking. The absence of any development in Islam of engineering is suggestive. This is probably the chief immediate explanation of the lack of advance in physics.

The Arabian failure in engineering is reflected in the personal story of Alhazen. He was engaged by the Caliph al-Hakim to discover a method of regulating the annual Nile inundation. He failed, and had to feign madness to save his life.

35

SCIENCE AND MUSLIM SOCIETY

The society which supported the technique and culture of Islam had several notable features. It existed in an area which stretched from Spain to India, and lay almost entirely between the twentieth and fortieth degrees of latitude, that is, just north of the tropics. This area contained an immense length of coastline and many navigable rivers. Its arid lands presented the dangers of thirst, starvation and sand-storms to transport, but were more easily traversed than the muddy and forest-covered lands of western Europe. Apart from the short isthmus of Suez, Muslim ships could sail almost directly from one end of the empire to the other without passing out of sight of land.

These conditions were favourable to transport. As the area contained many ancient and semi-independent civilizations each producing some characteristic products, there were plenty of materials for exchange. In addition, the Arabs had originally been nomadic, and their religion ordered them to make pilgrimages to Mecca. The growth of trade was assisted by this tradition of movement and favourable conditions of transport, and was facilitated by the existence of a universal language.

The Muslims accomplished many wonderful travels. In the middle of the fourteenth century, Ibn Battuta of Morocco visited Asia Minor, Russia, India, the Maldives and China. On his return, he met a man south of the Atlas Mountains whom he had seen in China.

Their merchants imported "sables, miniver, ermines, the fur of foxes, beavers, spotted hares, and goats; also wax, arrows,

birch bark, high fur caps, fish glue, fish teeth, castoreum, amber, prepared horse hides, honey, hazel nuts, falcons, swords, armour, maple wood, slaves, small and big cattle" from the Northmen on the Volga. Tens of thousands of Arabian coins of the seventh century have been found in Sweden, taken home by the Northmen. Slaves were imported especially from the Slavonic peoples, and from Spain. The spread of Islamic culture was assisted by those who returned. Gold was imported from Africa, and musk, aloes, camphor, cinnamon, indigo and other Oriental products, such as oranges, lemons, apricots, spinach and artichokes, were exported to Europe.

This trade led to the development of commercial technique. The influence of this on the growth of algebra has already been mentioned. The forms of banking were improved. The cheque, whose name is derived from an Arabic word, was introduced, and one for 42,000 dinars was seen in Morocco before the end of the tenth century. Other commercial words of Muslim origin are "tariff," "traffic," "risk," "tare," "calibre," "magazine" and the German *Wechsel* for exchange. Joint-stock companies were formed between Muslims and Italian Christians.

There was a considerable industrial besides the trading development. The textile industries were outstanding and have given the names of their products, such as muslin, damask, gauze, cotton, satin, chintz, shawl, fustian, taffeta, tabby, and lilac, to the modern world.

Industry was conducted by the rulers of the state, and not by individual capitalists. The workers were organized in guilds, but had the social status of slaves. The magnificent pile carpet from the mosque at Ardabil, now in the Victoria and Albert Museum in London, is signed "The work of the slave of the threshold, Maqsud of Kashan, in the year 946" (A.D. 1540). Under these conditions, the quality of craftsmanship reached high distinction, but the industry lacked free capital and individual initiative, and presently declined in competition with Europe.

The Muslim development of sea trade and navigation is also reflected in the words contributed to modern vocabularies. "Admiral," "cable," "average," "sloop," "barque," and "monsoon" are all Arabic words. The Muslim pilots prepared improved sea maps and instruments through their experience, and one of them conducted Vasco da Gama from Africa to India on his famous voyage. They were the forerunners in geographical discovery and world trade.

The Muslims learned how to manufacture paper from Chinese workmen whom they found in Samarkand when they captured the city in 704. The first paper mill at Baghdad was founded in 794.

One of the earliest recipes for gunpowder is given in a Latin work of 1300, which is probably a translation of an earlier Muslim work. It consists of "1 lb of live sulphur, 2 lb of charcoal from the lime or willow, 6 lb of saltpetre. Let the three substances be very finely powdered on a marble slab." Descriptions of incendiary and phosphorescent substances, and Greek fires (mixtures of petroleum, lime and other materials which will burn under water) are also given. Incendiary powders and substances which colour flames were a valuable part of the equipment of magicians who wished to impress the public. Some of these, which would be mildly explosive, may have been known to the Chinese and Indians at very early dates, but it seems probable that the Muslim alchemists, with their high chemical skill, improved the recipes, and made a large contribution to the invention of explosives.

The chief Muslim contribution to science was the revival of the knowledge of Greek science, with important additions in mathematics and chemistry, and lesser additions in astronomy and medicine. The contributions to engineering, physics and experimental biology were small. These features of Muslim science reflect the character of Muslim society and its economic system. The predominant economic interest of Islam was trade in goods produced by poor peasants, hunters, and

slaves. The interest in trade stimulated the study of arithmetic and algebra and of the qualities of materials, which led to chemistry. The demand for currency created by the expansion of trade stimulated the search for gold and encouraged the efforts of alchemists to transmute the base metals into it.

The slave status of the craftsman and mechanic, and the disrepute of manual work, as in Graeco-Roman civilization, hindered the development of mechanics. The lack of free capital for industrial production prevented the search for methods of increasing the remuneration of industrial investment. The controllers of industry were also the rulers of the state. As such, they had virtually unlimited wealth, and therefore had no strong incentive to efficiency. As skilled mechanics did not possess capital, they could not finance experiments in engineering. The study of machinery could not develop in these conditions. The background of mechanical knowledge necessary for experimental physics could not be accumulated, nor could craftsmen accumulate capital which would give them initiative to seek improvement and means and leisure to conduct experiments. The same lack of respect for manual work, reinforced by the religious prohibition of dissection and pictorial representation of living things, prevented the growth of experimental biology. In addition to these social circumstances, the Islamic Empire, like its classical predecessors, had a warm climate and was poor in wood and coal, so convenient sources of energy for exploitation as power were not easily available.

Islam revived ancient science, and made some considerable additions, but her social system prevented her from creating the balanced method of modern science, which depends on a combination of theory and experiment. This cannot be achieved without equal respect for each of them. Muslim scientists largely repeated Graeco-Roman science, and like it, became sterile, because the organization of Muslim society was fundamentally similar to Graeco-Roman society. The two societies and the two sciences died from the same social diseases,

of which slavery and the lack of free capital were perhaps the most important.

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36

THE SHAPE OF WESTERN CIVILIZATION IS FORGED

The first great barrier to the Muslim expansion was presented by Constantinople. This city was founded in A.D. 330 as the new capital of the Roman Empire and of Eastern Christianity. Its site as a military and trading centre was incomparable. It was gradually provided with very strong fortifications, and its population was minutely organized for war and civic life. Owing to the strength of the Byzantine organization, leadership was of less importance than usual, and the city could afford frequent changes of emperors without endangering its security. The walls of the city were of immense strength, and great underground reservoirs and cellars within the city provided stores of water and food large enough to outlast any siege. The Byzantines had a relatively small but expensive and highly trained professional army. They specialized in heavy cavalry. These Caballarii wore steel caps and mail shirts, with steel frontlets. They carried linen and wool cloaks to cover the armour according to the weather, and each man had a sword, dagger, bow-quiver and lance. Their introduction of iron horseshoes in the ninth century has already been mentioned. The Muslim armies were very large, but man for man their cavalry was no match for the Caballarii.

The Byzantines supported their expensive army by the profits of trade and industry. Their ships dominated the Black Sea and the northern Mediterranean, and the goods exchanged between East and West and North and South passed through their customs, all imports and exports being taxed at a flat rate

of ten per cent. In the sixth century they sent two Nestorian monks to China to steal the secrets of the cultivation of the silk-worm, which they brought back hidden in their hollow staves, and established a silk industry whose processes were concealed from Europe for centuries.

This powerful military, commercial and bureaucratic state protected Greek literature and language from 330 until 453. For 1,123 years it was an impregnable museum of Greek culture. Its copyists supplied a large part of the Greek scientific manuscripts which provided the basis for the Muslim science created from the eighth century onwards. The Muslims were interested only in medicine, science and philosophy, and ignored poetry, drama and history. The second cultural fertilization accomplished by the Byzantines occurred after 1453, when they had to flee to Europe and brought Greek literature with them. This movement, with which the Renaissance is traditionally so closely connected, was humanistic, as Greek science had already reached Europe through Islam. The Renaissance, in so far as it is regarded exclusively as a result of the fall of Constantinople, is not very interesting for science. The cultural effects of the flight from Constantinople were rather narrowly literary, and on the whole may have been unfortunate.

The Muslims began in 653 to organize combined attacks by sea and land on Constantinople. After incessant activity, their fleet appeared before the city in 674, and their armies attacked by land from April to September without success. The Byzantines counter-attacked the Muslim ships with fire-ships provided with Greek fire, the incendiary material, mentioned in an earlier chapter, which will burn under water and cannot be extinguished when alight. It is said that it was invented by a Syrian architect named Callinicus, and its composition was kept secret for many centuries.

The Muslims found their second great barrier in France. They conquered Spain in 711, and advanced into France, where

they were defeated by Charles Martel at the battle of Poitiers or Tours in 732. Charles' foot-soldiers withstood the attacks of the Muslim cavalry, which had previously proved almost invincible. The success of the Franks was not due to the superiority in military skill, but rather to the circumstances. The Muslim army contained few Arabs and consisted mainly of converted Berbers and Spaniards. These heterogeneous troops were led into a northerly region colder than those to which they were accustomed, so they would not have been able to make a sustained campaign without adaptation to a different climate. The Byzantines had noted that the Muslim cavalry was dispirited in cold and rain, and used this knowledge in their tactics against them. The Muslims had not contemplated such extensive changes, and their campaign was a raid rather than an invasion. As their empire was now so large, they tended to look inwards and enjoy their gains, and did not prosecute campaigns on their most remote frontiers with maximum ardour.

Their expansion in the West was halted exactly one hundred years after the death of Mahomet. Shortly afterwards, they began to devote more of their energy and wealth to the development of trade, science and culture, and they accomplished as much in this field in their second century as they had by conquest in their first. When this internal development of civilization had gathered momentum, the Muslims became less interested in further conquests.

Constantinople, Poitiers, and natural barriers, combined with the effects of its own vast size, settled the frontiers of Muslim civilization; and encouraged an internal development of its qualities. The determination of permanent frontiers between Islam and Europe had profound effects on Islam, but even profounder effects on Europe. It destroyed the internal communications, and hence the unity of the Roman Empire. With the coasts of Syria, Northern Africa and Spain under Muslim control, and the remaining coasts harried by Muslim galleys,

Christian shipping and trade in the Mediterranean were very much reduced. The Muslims, unlike the barbarian invaders of the Roman Empire, were not assimilated, owing to their sharp difference in religion, so their frontiers with Christian countries became almost impenetrable barriers. The connections between Rome and Constantinople were severed, and the western and eastern parts of the old Christianized empire fell away from each other, and henceforth developed independently.

This event, due to the Muslims, marked the end of Graeco-Roman civilization. Western Christianity was now forced to develop its own life, or be extinguished. As it was dominated by Charles Martel and the Franks, owing to their victory, it developed under the forms of Frankish society. This was the beginning of modern Europe. As Pirenne says: "A new Europe was created with the rise of the Frankish Empire, in which was elaborated the Western civilization which was one day to become that of the whole world."

The social forces that have created modern science were released by the changes which occurred in Western European society when it became isolated and was forced to develop its own potentialities.

37

THE EMBRYO OF THE MODERN WORLD

The suppression of Christian navigation in the Mediterranean by the Muslims destroyed the foreign trade and communications of Western Europe. Ports such as Marseilles, and trading towns on rivers in the interior, decayed through the lack of the materials of commerce. The remnants of the centralized Roman administration disintegrated, and the ancient offices, law courts, schools and posts were closed. The framework of the imperial system disappeared. The social classes which survived were the great landowners descended from the owners of the Roman latifundia, and a population descended from Roman *coloni*, or peasants who were partly free and partly attached to the soil. Industry was starved by lack of supplies. Manufacture and construction ended, except on a small domestic scale, and with them the demand for slaves, the pure engines of labour. No one not connected with agriculture was needed.

The landowners under the Roman Empire were private persons, and their personal wealth did not legally give them any political power. Everyone was theoretically subject to the Roman laws. When the Roman system had dissolved, there was no longer any legal curb on their power. In addition, owing to the destruction of trade, land was the sole form of wealth, so the surviving landlords had no wealthy competitors for power. They began to remould the political forms of society in their own interests. They increased the ties of the peasants to the land, and gradually converted numbers of free men into serfs. Though they lowered the status and restricted

the freedom of a large part of the poorer classes, they did not re-establish slavery. The decay of social organization had made the management of slavery more difficult. There was no longer any efficient Roman service for the capture of escaped slaves, and in a scattered agricultural society complete supervision was impossible. The allowance of some freedom to agricultural workers could not be avoided. The net increase in human freedom gained by the transition from classical to feudal society may be regarded, in some degree, as a concession made by government to save society when it was in danger of complete disintegration. This event seems to suggest that when the survival of society is seriously threatened, the most powerful stimulus which can be given to its members is an increase of freedom. Gibbon long ago observed that the poverty of the barons "extorted from their pride those charters of freedom which unlocked the fetters of the slave, secured the farm of the peasant and the shop of the artificer, and gradually restored a substance and a soul to the most numerous and useful part of the community."

Under the Roman system the law on the territory of landowners was administered by independent state officials. When the system decayed and the officials disappeared, the landowners appropriated the administration of law on their own estates. As combined owners and magistrates, their power was much increased. While this was happening, the destruction of trade eliminated the possibility of taxation, so that the Merovingian kings, who had become the dim successors of the emperors, could no longer finance an administration. Their power decreased as that of the landowners increased, and finally slipped into the hands of the largest landowner.

The transference was effected by Pippin. He made an alliance with the Church to obtain moral sanction for his usurpation of the throne of the Merovingians. As successors of the emperors, their power had been purely secular, and based on earthly sources. Pippin acquired religious significance for his

title. His coronation was the first consecrated by the Church. Unlike his predecessors, he was a sacerdotal figure besides a king, and claimed that he was called not merely to rule the earth, but to rule it according to Christian morality. Religion was combined with the State, and only those who were Christians could be members of the State. Excommunication became equivalent to outlawry, and furnished the instrument which established the political power of the Church in the Middle Ages.

Charles Martel, who withstood the Muslims, was Pippin's illegitimate son. He had been impressed by the Muslim cavalry at Poitiers, and determined to imitate it. As there was little fluid wealth in the new feudal society, his foot-soldiers could not buy and support horses. Land was the only form of wealth, so he granted them pieces of land sufficient to support a horse, on the condition that they would mobilize for war at his order. He did not scruple to expropriate Church property for these ends, and strained the new bonds between Church and State. But he had adapted the organization of the army to the economic system of feudalism. His reform established the military and political power of the landed aristocracy, and created chivalry.

Charlemagne, who was Charles Martel's grandson, conquered the whole of Central Europe with this chivalry, and the alliance of religious and political power. He had great character and ability, and attempted to establish an ideal feudal society harmoniously regulated in all of its divine and human aspects. He compiled manuals on the proper management of estates. One of these gives a list of the craftsmen needed on an estate in his day: "blacksmiths, goldsmiths, carpenters, swordmakers, fishermen, fowlers, soap-makers, men who know how to make beer, cider, perry and all other kinds of beverages, bakers to make pasty for our table, netmakers who know how to make nets for hunting, fishing and fowling, and others too many to be named."

He reformed writing and created the script which became the model for modern printers. He encouraged education in church schools to prepare men for administration in the State, and he founded the monetary system of pounds, shillings and pence, which survives in British currency.

The result of this inspired activity was disappointing. As cities had disappeared with the decay of the Roman Empire and the growth of feudalism, there were no centres where wealth could accumulate. Charlemagne and his court travelled perpetually from estate to estate, consuming the contents of the barns and then moving on. The administration had regressed from the sedentary Roman type established in cities, and had become nomadic. The feudal empire was invertebrate. The unifying monetary and cultural reforms were not supported by a firm administrative skeleton, or nourished by a sufficient flow of commerce, and they soon disintegrated.

The coasts of Charlemagne's empire were sealed on the south by the Muslims, and on the north by the Northmen. The foreign trade which might have provided the means for the construction of a vertebrate state had ended in the eighth century and did not revive until the eleventh.

commercial technique was learned through this contact, owing to the mutual religious hostility.

The effective channel through which Europe received Muslim science was Moorish Spain and northern Africa. Toledo was retaken from the Muslims in 1085. A large number of Arabic manuscripts were left in the city, and a mixed population of Moors, Jews and Spaniards, who knew Arabic and Latin. Translation of the Arabic manuscripts into Latin was organized on a considerable scale, and enterprising scholars from all parts of Europe came to learn Muslim science and read Arabic translations of Greek works hitherto unknown in Latin. Many of these scholars had a passion for translation. Gerard of Cremona journeyed to Toledo to read Ptolemy's *Almagest*, which was not available to him in Latin. He was astounded by the wealth of Arabic words and began translating them with incomparable ardour. He completed nearly one hundred translations before he died in 1187, including Euclid's *Elements*, Ptolemy's *Almagest*, the works of Galen and Hippocrates, and Aristotle's *Posterior Analytics*.

What was the motive that sent Gerard of Cremona, and other scholars, many of whom were Englishmen, to study in Spain? It was the energy generated by the developing society in medieval Europe. The crusades had created a new trading class in the Italian ports. They had also stimulated pilgrimages and a general movement of soldiers and pilgrims throughout Europe which carried trade with it. The aspirations of the scholars were an expression of the hope created by the increasing prosperity. Many of them were Englishmen. Adelard of Bath made the first Latin translation of fifteen books of Euclid from Arabic about 1126. Contrary to the general belief, he was not a monk. He certainly visited Sicily and Syria, and probably Spain. He also translated al-Khwarizimi's astronomical tables, revised for the meridian of Cordova by Maslama.

Adelard composed scientific dialogues for the instruction of his nephew. He rejected unquestioning faith and advocated

scientific investigation. He attacked excessive reliance on authority, for "I learned from my Arabian master under the leading of reason. . . . If you want to hear anything more from me, give and take reason. For I'm not the sort of man that can be fed on a picture of a beef-steak."

He explains that reason is not sufficient to solve the problems of the universe, and that observation and measurement are necessary. "Who has ever comprehended the space of the sky with the same sense of sight? . . . Who has ever distinguished minute atoms with the eye?" As Thorndike comments, such questions as these express the need for the telescope and show that the conditions for its invention were maturing. He clearly states the principle of the indestructibility of matter. "And certainly in my judgment nothing in this world of sense ever perishes utterly, or is less today than when it was created. If any part is dissolved from one union, it does not perish but is joined to some other group." He discusses the behaviour of water imprisoned in an enchantress's inverted jar, and unable to flow out until air bubbles through the lower aperture. His explanation contains some conceptions resembling chemical affinity, and the experiment, which he describes carefully, is an example of the debt of experimental science to magic. Robert of Chester translated al-Khwarizimi's algebra into Latin in 1145, under the title *Liber Algebre et Almucabala*, and introduced this new branch of mathematics to the Western world. The connection between England and Christian Spain was not purely cultural. It was strengthened by the marriage of Alfonso VIII to Lenora, a daughter of Henry II, at the end of the twelfth century.

The first original European work on algebra was published by Leonardo of Pisa in 1202. The city of Pisa, as the leading port of embarkment for the crusades and a growing trading centre, had custom-houses in many Christian and Muslim Mediterranean ports. Leonardo's father was the controller of the Pisan custom-house at Bugia in Barbary, and his son was educated by a Muslim teacher. He became acquainted with

al-Khwarizimi's algebra, the Arabic numerals and decimal calculation. He travelled in Egypt, Syria, Greece, Sicily and southern France, and learned the various methods of calculation used by the merchants in those countries. He published a treatise in 1202, named the *Liber Abaci*, containing an exposition of the best methods of calculation, and the elements of algebra. The work was composed in fifteen chapters. The first seven dealt with arithmetic and its operations. The eighth dealt with the Prices of Goods, the ninth with Barter and the tenth with Partnership. Other chapters were devoted to solutions of problems, square and cube roots, and mensuration and algebra.

Leonardo contributed more than any other man to the establishment of the decimal system in Europe. His knowledge was derived from his contact with commerce, and it was not esteemed in the orthodox universities, especially at Paris. He had great mathematical ability and made original contributions, especially in the theory of numbers. The Emperor Frederick II, King of Sicily, visited him in 1225, and conducted the first mathematical tournament in his honour. This was the forerunner of the competitions and challenges which continued down to the time of Newton, and show the influence of feudal social forms even on mathematics. The competitors were asked to find a number of which the square, when increased or diminished by 5, would remain a square. Leonardo gave the fraction $\frac{41}{12}$, which is a correct solution. The second problem was the solution of the cubic equation $x^3 + 2x^2 + 10x = 20$ by Euclidean methods. He showed that solution by these methods was impossible, but gave an arithmetical answer correct to nine places of decimals.

Frederick had an extraordinary part in the encouragement of science in the thirteenth century. He was of Norman descent, and ruled Sicily, which had the most advanced system of agriculture in Europe, and a population of more than one million. It had formerly been a Byzantine and then a Muslim colony,

and had inherited from these civilizations a despotic government, with a competent civil service. As a meeting place of so many civilizations, Sicily was an admirable centre for the communication of Greek and Muslim learning to the West. Frederick lived from 1194 to 1250. He was a despot, but combined a love of power with an interest in art, learning, experiment and magic. The conflict of cultures in his country provided suitable soil for scepticism, and he was reputed to be an unbeliever. The opinion that Moses, Jesus and Mahomet were impostors was attributed to him, and Pope Gregory IX accused him of heresy and blasphemy. This opinion had previously been fathered on others to destroy their reputations. He had bizarre habits, and a harem of Muslim women. He denied the accusations of heresy, and collaborated with the papacy in the creation of the Inquisition. There is little doubt that he was privately atheistical, and persecuted heresy in others from political motives. Lying, torture and perjury were his favourite political weapons, and burning at the stake as a punishment of the Inquisition was first officially recognized in ordinances made by him.

Besides encouraging translators, he had a personal interest in experimental research. He studied falconry and natural history, and was accomplished in the mechanics of architecture. Like Alexander the Great, he used his royal administration to collect scientific information, and provided a remarkable example of the pursuit of research by governmental agencies. He collected scientific information by questionnaires addressed to scholars in Egypt, Syria, Irak, Asia Minor and Yemen.

Frederick freely criticized Aristotle's knowledge of natural history, especially in connection with falconry. He said that he depended too much on hearsay, and must be corrected from personal observation. He "rarely or never had experience in falconry, which we have loved and practised all our lives."

He tested the artificial incubation of hens' eggs. He brought experts and ostrich eggs from Apulia to make similar tests with

them. He exploded the fable that geese come from barnacles by sending to the North for barnacles and making the experiment. He concluded that the story arose from ignorance of the nesting place of geese. He sealed the eyes of vultures to discover whether they hunted by sight or smell. He shut a man in a wine cask to prove that his soul died with his body. He had two men disembowelled, one after exercise and the other after sleep, to show the different effects of exercise and sleep on digestion. He reared children in silence to see whether "they would speak Hebrew first, or Greek, or Latin, or Arabic, or at least the language of their parents; but he laboured in vain, for the children all died."

He assisted education by founding the University of Naples, where Aquinas studied. He ordered the translation of the medical works of Avicenna, which remained the standard authority for five centuries, and he laid down that medical students should study logic for three years before commencing medicine. He ordered that surgeons should study human anatomy for one year before graduation. His laudable instruction failed, owing to the overwhelming weight of medical literature and the social status of surgeons. They were regarded as handicraftsmen, and the inferiors of physicians, from whom they were supposed to take orders. Their observations were therefore deemed beneath the dignity of record in literature.

Though accused of scepticism in religion, he passionately believed in magic. Michael Scot and Theodore of Antioch were his official astrologers, and he conducted his military campaigns with their advice. When he was defeated by the Pope's allies before Parma, his enemies exulted in their destruction of his troop of magicians and devotees of Beelzebub and the demons. He became identified with Antichrist though he led the fifth crusade and became king of Jerusalem in 1229. The legend arose that he had never died, but slumbered under a hill. The hero's part in this story was transferred in later times to Frederick Barbarossa.

Frederick II has been described as the first modern man to ascend a throne. He resembled the princes of the Italian Renaissance with his rationalism, experimentation, political cruelty and superstition. The dictators of the twentieth century lack his interest in culture. Perhaps that is because he was the forerunner of a rise in civilization, whereas they are the morticians of a declining civilization.

The history of Frederick II's activities shows that the relation between toleration and the progress of science is not simple.

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MANUAL LABOUR ACQUIRES NEW REPUTE AND MECHANICS ADVANCES

The scholars who journeyed in search of Arabic science received their impetus from the social energy created by the developing medieval society. This expressed itself in tremendous constructive works. The French built eighty cathedrals and five hundred churches between 1170 and 1270. Henry Adams has estimated that their cost was equivalent to the sum of one thousand million dollars. In the outlying countries, from England to Hungary, building was not much less intense. The social atmosphere of this activity has been recorded by Archbishop Hugo of Rouen in his description of the great cathedral at Chartres. This is perhaps the most wonderful religious building raised in Europe. It is made of very hard stone brought in large blocks from quarries five miles away. Hugo states that the inhabitants of Chartres combined to aid in the transport of materials. The associations admitted no one who had not been to confession, renounced enmities, and reconciled himself with his enemies. After that had been done, and the association formed, a chief was elected. Under his direction, the wagons were hauled by the people in silence and humility. The work was done with feverish rapidity. Hugo comments: "Who has ever seen!—Who has ever heard tell, in times past, that powerful princes of the world, that men brought up in honour and wealth, that nobles, men and women, have bent their proud and haughty necks to the harness of carts, and that, like beasts of burden, they have dragged to the abode of Christ these

wagons, loaded with wines, grains, oil, stone, wood, and all that is necessary for the wants of life, or the construction of the church?"

The multitude of *hauliers* remained silent, even when a thousand and more were attached to the chariots. When they halted on the road nothing was heard except the confession of sins and suppliant prayers. At the exhortation of the priests they forgot all hatred and discord, debts were remitted and the unity of hearts was established. The contribution of anyone who refused to pardon an offender was instantly thrown from the wagon and he himself was ignominiously excluded from the society of the holy. Priests presided over each chariot and recited prayers during the rests. Their trumpets were sounded for the resumption of the haul, and the march was made with such ease that no obstacle could retard it.

The conditions of work at Chartres are in notable contrast to those of antiquity. There were no slave-drivers standing over the human *hauliers* with whips, and members of all social classes bent their necks to the harness of carts. Manual labour was being made reputable. "Who has seen!—Who has ever heard tell" of such a thing "in times past?"

A large part of the wealth required for this construction was supplied by the inhabitants of the towns growing on the trade routes revived by the crusades, and around the new churches. In the cathedral of Chartres, built in its present form between 1195 and 1240, the seven great windows were donated by the Drapers, Butchers, Bakers, Bankers, and other guilds, and none by noblemen. This bourgeoisie was exerting its due power, and even coming closer than the feudal lords to the most sacred centres of the contemporary society. It was achieving a new social status and repute. Its sons could not enter the feudal nobility, whose membership was determined by ancestry, but they could enter the Church and had a fair chance of attaining rank according to their ability. Piety satisfied the conscience of this bourgeoisie, and strengthened its ties with the Church,

which could provide political besides religious careers for its sons.

These members of crafts, trades and professions now acquiring such a solid position in society were the descendants of the medieval servants listed by Charlemagne. They were small masters employing one or two journeymen and apprentices. They owned their raw material and the profit on the sale of their products was exclusively theirs. Their customers were fellow citizens and local peasants. Individual craftsmen working on a small scale under these conditions were very insecure, owing to the limits of the local market. They early organized themselves into guilds to regulate competition and guarantee every member a living. Rules governing the conduct of crafts were gradually evolved. The price of products was fixed. Working by artificial light, the use of unusual tools or the modification of traditional technique, the employment of more than the usual number of workmen, and of wives and young children were forbidden. The most severe prohibition of all was applied to advertisement. This was absolutely forbidden.

The guild rules repressed technical innovation, but they strengthened the social status of craftsmen and manual work. The social energy accumulated by the latter development proved ultimately to be stronger than the bonds placed on technical invention by guild rules. The medieval crafts gave encouragement to the development of technique less by direct contribution than by elevation of the social status of craftsmen. Even when a medieval industry achieved unusual dimensions it made little technical progress. The textile industries of Venice and Bruges had a large export trade, but their technique was not substantially better than that of ancient Egypt.

The construction of the new churches presented considerable technical problems. The weights to be moved were large, even if smaller than many handled by Egyptians and Romans. The invention of the pointed arch and stone vaulting presented problems in geometry and statics which would have been more

complicated than those solved by the ancients if they had been solved exactly. It seems, however, that the medieval architects reached their greatest achievements by experience and not by analysis. Improvement of design was learned empirically in the construction of one church after another, and from defects in construction revealed by time.

The technical knowledge of a medieval architect has been preserved in the precious notebook of Villard de Honecourt. He was the architect of the Cathedral of Cambrai, part of which had been paid for by Elizabeth of Hungary. After the Tartar invasion of Hungary in 1242, her brother King Bela sent for Villard to rebuild churches. He made sketches of remarkable things he had noticed in his travels between 1243 and 1251. The width of a river is determined by pointing two horizontal sticks at an object on the other bank. The two sticks, which will be inclined at a small angle, are then fixed to a board, and laid on a smooth field. An observer looks along the sticks, and an assistant holds a post until the place which both sticks point at it is found. The distance between the post and the sticks is equal to the width of the river and may be directly measured. The height of a tower is obtained by placing a right-angled isosceles triangle, or half-square, in a vertical plane, with one of the short sides in contact with the ground. The triangle is slid about until the hypotenuse, or long side, is in line with the top of the tower. The height is equal to the distance of the triangle from the base of the tower.

Both of these methods are very crude and inaccurate. Villard gives a solution of a problem in which a man has to place an egg under a pear hanging on a tree so that if the pear falls it will hit the egg. Two posts are stuck in the ground so that they and the pear are seen to be in the same vertical plane. The feet of the posts are joined by a string. The operation is repeated with another pair of posts, and the egg should be laid at the point where the two strings intersect.

He gives some geometrical methods of about equal merit for

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A NEW SYSTEM OF SOCIAL CLASSES AND ITS EFFECTS

The new society, which had been virtually isolated for three centuries, flourished particularly well in northern France. The grassland was suitable for the support of horses, and its subdivision had been carried further than in other countries. The climate was temperate, and suitable for the wearing of heavy armour and continuous exercise. One-tenth of the population were minor noblemen and hence professional horse soldiers. Many of these were of Scandinavian descent, though their assimilation was so complete that no Scandinavian word survived in the Norman language. The Normans retained nothing of their Scandinavian ancestors except an extraordinary spirit of adventure.

Their military technique was perfected during three centuries of evolution. The minor noblemen with just enough land to support their personal arms engaged in incessant tourneys. Their sons learned to fight as soon as they could mount a horse. All civil and intellectual technique disappeared, except in a few monasteries, where memories of Roman technique and trade survived.

This Norman military society was able to undertake great aggressions in the second half of the eleventh century. It invaded Sicily in 1061, England in 1066, and Palestine on the first crusade in 1099. It became the military instrument of the papacy, which was now the greatest political power in Europe, owing to the weakness of central government under feudalism.

The Church's possession of political power enabled it to

use the Normans for its own ends. It launched them against the Muslims in Palestine with the purely religious aim of securing the holy places of Christianity. The Norman knights were unlettered, brutal and pious. They had strong sentiments of devotion and honour. They scrupulously respected the right of sanctuary. They regarded their word as sacred, and interpreted all relations between man and man from the personal point of view. They had no sense of discipline and obedience, and immediately rebelled if injured. They expressed their opinions with the utmost boldness and plain speaking. They engaged in no productive labour, and had extreme contempt for profit-seeking. These qualities were based on their economic and political independence.

Norman society was very different from the contemporary Muslim society. It had little science and technique, apart from that of warfare. But it was free from political absolutism and pure slavery. It contained a relatively large number of small landowners who created a tradition of the independent gentleman who thinks for himself and does things for their own sake without thought of profit. The Normans made few scientific discoveries, but their development of a society with these traditions was a contribution towards the creation of the social conditions under which science can grow continuously. The Muslims failed to create the social conditions in which new major science could take root and grow, in spite of their brilliant revival of ancient science.

The second great service to future science performed by Norman and feudal society was equally indirect and unconscious, and very different in character. The crusaders in Palestine required transport and victuals. These were supplied by merchants and seamen of Pisa, Genoa and Venice. Christian trade and navigation were revived, and from that time, eight hundred years ago, they have expanded nearly continuously. The crusaders brought Europe in clashing contact with Muslim civilization in Palestine, but very little of Muslim science and

marking stone to be cut for arches, and a number of vigo: ıs sketches of draped human figures from the life for stone carvings, and a sketch of a lion, which he specially notes as drawn from the life. His perspective is wrong, but some of the figures show high artistic power. He gives an elaborate drawing of a well-known type of perpetual-motion machine.

The technical part of these subjects is disappointing. There are, however, two other entries of extraordinary interest. One is a sketch of a self-acting sawmill driven by water power. The saw hangs from a long elastic pole. Four legs stick out of the axle of the water wheel, and each peg depresses the other end of the saw as it goes round. After a downward stroke by a peg, the saw is pulled back by the elastic pole. This is the first power saw recorded in history, apart from a possible obscure reference to one that existed on the Moselle in the fourth century.

The second sketch is of first-rate importance. It gives the design of a machine "to make an angel point with his finger always to the sun." It is the first record of an escapement motion for preserving a constant speed of rotation. The drawing is rough, and the true nature of the machine remained unrecognized for a long time. A rope is wound round the spindle carrying the angel. One end passes over a pulley and bears a weight. The other end is passed round the axle of a wheel, and then through its spokes, and finally over a pulley, where it is attached to a weight. If one weight is heavier than the other, it will tend to fall and pull the rope so that the spindle rotates. But the axle of the wheel will also rotate, and this makes one of the spokes drag the rope sideways. This stops the fall, and also the rotation of the wheel, which now recoils. The rope is released, slips a bit further, and is again held, and so on.

This contains the principle of the fundamental mechanism of the mechanical clock. It seems probable that Villard had seen the machine somewhere on his travels between France and Hungary.

The improvement of the clock was the chief inspiration of mechanical invention for four centuries. The invention in the thirteenth century of the most difficult principle in clock mechanism suggests that modern mechanical technique evolved from something that began in medieval civilization. The discovery of the escapement principle was not an isolated innovation. An anonymous treatise on statics which contained the first correct discussion of the equilibrium of a balance was written in the thirteenth century. It has been attributed to Jordanus, who joined the Dominican order in 1220, but it is not by him.

A weightless bent lever with arms of unequal length is freely suspended at the corner. The ends of the two arms are at equal distances from a vertical line through the point of support. The author asks whether the lever will remain in equilibrium if equal weights are attached to the ends of the arms. He considers the effects of small displacements of the lever from its original position, and shows that they are impossible if no external force is applied.

Hitherto, no writer on the lever had clearly understood that the forces on the arms need not act at right angles to them. In practice, ropes were tied to levers and hauled in directions not at right angles to the arms, but theorists had not started from what happened in practice. They had followed Archimedes, and tried to extend the principle of balance, seen intuitively in a straight horizontal symmetrical lever with equal weights, to levers with unequal arms. Owing to their start from the horizontal lever with forces acting at right angles to its arms, they tended to assume that forces always must act at right angles to arms, and were unable to arrive at the generalized principle of statical moments.

The anonymous mechanician of the thirteenth century had used a principle of displacements which eliminated this assumption and contained a correct theory of statical moments. He had in fact published the first example of the use of the power-

ful principle of virtual work. His successors, from Leonardo da Vinci to Willard Gibbs, have founded theoretical mechanics on this principle.

As Usher has remarked, the subsequent study of the Greek texts of Archimedes, which occurred in the sixteenth century owing to the Renaissance, caused the medieval discoveries to be neglected, and threw back the knowledge of some parts of mechanics to a pre-medieval stage.

The Renaissance was motivated by a complex of forces, not all of which were beneficial to science.

40

THE PURSUIT OF GAIN IMPELS SOCIAL AND TECHNICAL DEVELOPMENT

The agricultural society of feudalism was self-supporting and stable. Its landlords, peasants, craftsmen, clergy possessed some security, and felt no powerful incentive to change. If the isolation from the rest of the world could have continued indefinitely, it might have remained unchanged for many centuries. But it was not completely sealed off by the Muslims and its other enemies. The Byzantine navy controlled the Adriatic and invited imports from its coasts. The lagoons off Venetia were a convenient source of salt, and fishermen who lived there and had no demand for salt from the self-supporting inland society were able to export their product to Byzantium. Their trade in this commodity grew considerably in the ninth century and they erected buildings on the islands in the lagoons. This was the foundation of the city of Venice. Owing to its peculiar position and activity it was outside the normal Western European feudal society, and from the tenth century its policy was purely commercial.

The development of Pisa and Genoa as ports of supply for the crusades started a little later.

The Venetian fishermen who received Byzantine silk for their salt, and the Pisan boatmen who sold food at extravagant rates to crusaders and received gold and jewels in payment could not consume their new property. They had to find a market for it. They could not do this within the recognized framework of feudal society. There was no transport for moving salable goods through feudal countries. The recognized

classes of landowners, peasants, craftsmen and clergy accepted the principles of feudalism, which were opposed to ideas of commercial profit, interest, and the use of money.

The new merchants of the coasts, who were a species of fisherman, adventurer and pirate, could not find agents in these classes to tout their goods through the feudal countryside. Only landless vagabonds would undertake this. These wanderers, who had nothing to lose and had picked up knowledge of the world in their wanderings, lived by their wits, listening for news of dearth and famine and rushing to sell dear what they had bought cheap. As they had no social status and security they were also without social duties and enjoyed the freedom of vagabondage.

Numbers of them spread through feudal Europe during the tenth century, and made their headquarters near feudal fortresses or bourgs, and in the communities surrounding cathedrals, many of which had been built on rivers and natural lines of communication.

At first there was no place in the feudal communities for this new class of turbulent merchants. They had to make their position. They gradually established it by their wealth and the stimulus their commerce gave to the places where they settled, and they formed guilds to protect their interests and ensure their social status.

Cities did not exist in feudal agricultural society, because the inhabitants were tied to the soil and were supported by it. The population was permanently scattered and had no motive for aggregation. Centres such as castles and cathedral towns were for protection and administration and had virtually no part in production. They contained small groups of craftsmen who supplied purely local needs and there was no stimulus to multiply their number.

The free, wild and vagabond merchants who began to settle these feudal centres in the tenth century were without roots in the soil and seemed scandalous to the feudal inhabitants.

They were followed by unattached craftsmen and labourers, who presently formed guilds in imitation of the merchants to protect their own interests. None of them could be returned to serfdom, because their owners were unknown.

Besides developing commerce, the merchants spread the idea of working for personal profit instead of feudal duty. Their commercial activity created a demand for craftsmen and labourers, and at the same time the peasants in the surrounding country learned the idea of initiative for personal gain. Numbers of them were attracted to the centres by the new demand for labour. The old bourgs or fortresses and the walled ecclesiastical communities were unable to accommodate the increasing population. The new free and vagabond community settled outside the walls of the bourg, which were presently surrounded by their houses. Then an outer wall was built around the houses, and the enclosed ring was named the nouveaubourg or faubourg. The inhabitants of the ring were named bourgeois in the eleventh century.

The bourgeoisie began to establish its own system of law within its faubourg. This was based on the principle of personal property, and was in conflict with feudal law. If a peasant who had deserted his lord was within their gates, the bourgeoisie would not surrender him. Punishments more brutal than those customary under feudal law were introduced to control their wild and grasping members and protect personal property.

As the bourgeoisie did not belong either to the noble or peasant classes, it did not share their class feeling, which was uniform throughout Europe. It evolved a new intense civic feeling and solidarity, which was expressed as strongly against the bourgeoisie of other cities as against local feudal lords.

The originally wild bourgeoisie settled down and developed its organization of guilds, and after its first struggle for status had been satisfied and the principles of its way of life accepted, it began to subscribe to the Church, and contributed magnificent gifts such as the altar windows at Chartres.

The growth of the bourgeoisie and its activities underr `ned feudalism. The increase in the circulation of money produced a rise in prices, and this lowered the real value of feudal dues. Many small landlords were ruined, and large landlords sought to bring virgin land under cultivation to restore their incomes. The Dutch lowlands were drained by new orders of monks who were prescribed to manual labour. The big undertakings led to the creation of the first large-scale agriculture since Roman times.

The urban demand for food gave a new stimulus to the peasant. Hitherto he had produced a definite quantity of food for local consumption only. Now he was encouraged to produce as large a surplus as possible and sell it at a profit to the town.

The increase in production due to the bourgeoisie stimulated the creation of new monastic orders. The Franciscans, who lived by begging, could not exist without surplus production, a principle incompatible with feudalism. They were the obverse of the new bourgeoisie. By pledging themselves to poverty, they atoned for the bourgeoisie's lust for gain, and became its conscience. In return, the bourgeoisie kept and favoured them.

The bourgeoisie wrested a position beside the nobility and clergy in the state. Progressive kings sought alliance with them against the nobility, and by their aid limited the political power of the landlords. This movement gradually destroyed feudalism and created the national state.

The new technique of commerce was evolved by the merchants in Italian ports and cities. They learned much from the Muslims of banking, bills of exchange, and money-lending, and devised improvements from their own experience. They introduced bookkeeping by double entry in 1394. They needed clerks to keep accounts. At first these could be supplied only by the Church and they wrote in Latin. This was inconvenient, for the bourgeoisie conducted its business in the local dialect.

They wanted persons who wrote in the local dialect, so they created a new class of educated laymen, who presently began to write secular literature in the vernacular. Through these scholars the bourgeoisie began to think and write for itself and it started to replace the feudal conceptions of life and nature by its own.

41

THE INTELLECTUAL WEAPONS ARE SHARPENED

The Church was the sole framework which prevented Western European society from relapsing into savagery in the sixth, seventh and eighth centuries. Education had passed entirely into its hands, and when Charlemagne sought trained servants for his government, he naturally turned to the Church to provide them. Under his stimulus many new cathedral schools were founded. As the Church controlled education, theology became and remained the chief subject of study, and provided medieval civilization with its characteristic unity.

When Western European society began to revive, a profoundly authoritative theology surrounded the new thinkers. It had apparently carried society through a period of extreme danger and was entitled to its prestige. This theology had been created chiefly by Augustine, through a combination of Christian dogma and Platonic philosophy. These two elements determined the content of subsequent medieval thought. As Harris explains, its history consists of the interaction of a permanent mass of church dogma with an increasing knowledge of ancient philosophy.

The written word, like Christian dogma, had also survived the social disintegration. At the beginning of the revival, when illiteracy was still nearly universal, it also enjoyed exceptional authority. Dogma, Platonism and the written word were virtually sacred.

The first and perhaps the most profound medieval philosopher was Erigena, who was born in Ireland in the ninth century. His philosophy was Neo-Platonic. He believed that

thought is the only ultimate reality, and that corporeal sensations are mere illusions. He had a sublime theory of orders of creation which was derived from Plotinus' scale of perfection. Erigena's thought was too difficult and original and made few converts.

As Brehaut says, the supernatural world appeared ordered and real to the thinkers of the early Middle Ages, while the world of the senses was deceptive and unreal. The exaltation and failure of Erigena's effort in thought may be compared with Charlemagne's in government. Both men in their spheres were too far in advance of contemporary development.

The next revival of thought occurred in the eleventh century, during the period of the Norman expansion and the founding of the bourgeoisie. It was less exalted, and concentrated on the problem of general concepts or universals rather than on Erigena's sublime orders of creation.

Is a general concept such as "humanity" a real substance which is always the same and pervades all individual human beings, or is it merely a class name for a group of particular men? Those of the former opinion were called "realists" and the latter "nominalists."

Roscellinus, who was a nominalist, pointed out that if the realists are correct then the three Persons of the Trinity are not three beings but one, while if the nominalists are correct, the three Persons are individual, and are three Gods.

As Harris says: "At this abominable tritheism the whole of Christendom stood aghast." This sort of wrangling was characteristic of the new scholasticism. The number of disputants rapidly increased with the increasing social prosperity in the eleventh century.

Anselm, who lived from 1033–1109, attempted to restate church dogma in the terminology of the new disputants, and was the first since Augustine (who wrote at the end of the fourth century) to write a systematic treatise on dogma. He was a man of profound faith who also appreciated the need for

rational explanation, so he tried to re-establish theology or he basis of two principles, one of faith and the other of argument. According to the first: "He who does not believe will not experience, and he who has not experienced will not understand." This resembles some of the notions of Bergson, and of those social philosophers who deny that it is possible to understand a social movement without taking part in it. His famous "ontological" argument for the existence of God asserts: "God is that being than whom none greater can be conceived. Now, if that than which nothing greater can be conceived existed only in the intellect, it would not be absolutely the greatest, for we could add to it existence in reality. It follows then, that the being than whom nothing greater can be conceived, that is God, necessarily has real existence."

The new logical enquiry was trenchantly described by Bérenger of Tours, who lived from 998 to 1088. "It is the part of courage to have recourse to dialectic in all things, for recourse to dialectic is recourse to reason, and he who does not avail himself of reason abandons his chief honour, since by virtue of reason he was made in the image of God."

This confident spirit was raised still higher by the famous Abélard, who lived from 1079 to 1142. He came to Paris in 1100, and immediately made a name by disputing with the leading teacher, William of Champeaux, who lectured in the school of the cathedral of Notre Dame. He was brilliant and aggressive, and attacked his opponents like an intellectual knight-at-arms.

Students were fascinated by his skill and personality, and flocked to his lectures. He received fees from three thousand at the height of his vogue. But his vanity and intellectual confidence aroused numerous enemies. The old-fashioned mystics such as St. Bernard, who felt that the truths of religion were known by intuition and not by reason, hated him. St. Bernard complained that "he sees nothing as an enigma, nothing as in a mirror, but looks on everything face to face."

Abélard claimed to explain God's motives. He said: "All that God does He wills necessarily and does it necessarily; for his Goodness is such that it pushes Him necessarily to do all the good He can, and the best He can, and the quickest He can. . . . Therefore it is of necessity that God willed and made the world."

He compiled in parallel passages, entitled *Sic et Non* (*Yes and No*), all the contradictory statements he could find in the Scriptures and Fathers, and he suggested principles by which they could be reconciled, but he did not offer any examples. This comparative method was first used by lawyers, who had rediscovered the codes of Justinian after a lapse of five centuries.

St. Bernard loathed this growth of intellectual criticism. He said that if these scholars had "once tasted true food of religion, 'how quick' they would be to leave those Jew makers of books to gnaw their crusts by themselves."

Abélard was watched relentlessly by Bernard and the orthodox. They secured the condemnation of his book on theology in 1121. He was shut in a monastery and rarely lectured again. Bernard became Pope, and in 1140 organized his final suppression. He had him accused of striving for an exclusive domination in the schools. "He treats Holy Scripture as though it were dialectics. It is a matter with him of personal invention and annual novelties. He is the censor and not the disciple of the faith: the corrector and not the imitator of the authorized masters." Like many other mystics, St. Bernard combined religious intuition with political cunning. He packed the court with Abélard's opponents in church politics, and had him condemned to silence. Abélard died two years later, in 1142.

The radicalism of Abélard's confidence in reason and love of novelty, and his egotism, have always disturbed conservatives. Haskins has described his lively but boastful autobiography as the portrait of the eternal radical by himself. And yet

Abélard's thought, as distinguished from his attitude of mind, was not radical, unless an advance towards the moderate Aristotelian realism of the thirteenth century, and away from extreme Platonism, is regarded as radical.

He expressed his view on the fundamental problem of universals thus: "When we say that Plato and Socrates are both men, we do not mean that there is a mysterious essence 'humanity' which, one and the same, gives being to both, but we mean that both have similar essences."

Very few of the works of Plato and Aristotle were available to Abélard. He was familiar only with the *Timaeus*, in which Plato applies his theory of ideas to science, and gives perhaps the least convincing of all his expositions of idealism; and with the Platonic early works of Aristotle.

Shortly after his death, the translations of the metaphysics and natural science of Aristotle, and his Muslim commentators, arrived in Western Europe, accompanied by Galen, Hippocrates and Avicenna in medicine; Euclid, algebra, perspective and optics in mathematics and physics, and Muslim astronomical tables based on the meridian of Toledo.

The contemporaries of Abélard had already become dissatisfied with dialectic. His student, John of Salisbury, had recorded that "experience taught me a manifest conclusion, that, whereas dialectic furthers other studies, so if it remain by itself it lies bloodless and barren, nor does it quicken the soul to yield fruit of philosophy, except the same conceive from elsewhere."

Daniel of Morley left Paris in disgust about 1180, and went to Toledo "to hear the wiser philosophers of the world." He attended lectures by Gerard of Cremona, and returned to England with the translations of various Muslim works.

Daniel's initiative in educative travel resembled Abélard's in philosophy. Both courageously advanced into new regions.

42

THE CHURCH TRIES TO ASSIMILATE SCIENCE

Albertus Magnus, who lived from 1206 until 1280, undertook the systematization of all the new knowledge in philosophy and science. He saw that the Greek and Muslim philosophy could not be merged with Christian theology, and began the separation of philosophy and theology. He noted that "natural science is not simply receiving what one is told, but the investigation of causes in natural philosophy."

Besides summarizing virtually the whole knowledge of his day, he made original observations and experiments, especially in biology and mineralogy. He and his colleagues proved by experiment that a cicada goes on singing in its breast after its head has been cut off. He considered that he had proved by experiments in a vessel that a turtle, though a marine animal, would not drink sea water. He disproved the assertion that ostriches eat and digest iron by offering them bits of iron. They rejected these, though they swallowed stones and bones cut into small bits.

Albert reflected the contemporary interest in observation of nature, exhibited in cathedral sculpture. As Mâle has noted, the depiction of foliage and fruit in Gothic sculpture is so exact that modern naturalists have been able to identify the plantain, arum, buttercup, fern, clover, celandine, hepatica, columbine, cress, parsley, strawberry, ivy, snapdragon, oak leaf and the flower of the broom, as among the original flora of modern France.

Villard de Honecourt depicted a lobster, paroquets, the spirals of a snail's shell, a fly, a dragonfly, a grasshopper, a lion, bear, swan and cat in his sketch book.

Albert was the most learned scholar of his day and the pride of the Dominican order.

The Dominicans presently discovered a youth with an extraordinary talent for learning who was the son of the Count of Aquino in Sicily. This was Thomas Aquinas. He was born in 1225, joined the Dominicans when he was sixteen, and was sent to study under Albert.

The first draft of the adaptation of the rediscovered Greek and Muslim knowledge to Christian dogma had been laboriously completed by Albert. Thomas assimilated this quickly and, while his mind was still young and fresh, began a more systematic, profound and polished treatment of the same problem, and especially the combination of Christian dogma with Aristotelian philosophy. The chief statement of his thought is in his *Summa Theologica*, the English version of which is published in twenty-two volumes. This was unfinished when he died in 1274, at the age of forty-nine.

Earlier Christian thought, both of the severely rational and of the mystically speculative type, was almost exclusively Platonic. Thomas therefore had to find foundations other than the Platonic and the mystical for his theology if he was to reconcile Christian dogma with Aristotelianism. He had the courage, which was rare in his time, to deny that the existence of God is self-evident, and had such confidence in his reason that he believed he had proved His existence by five conclusive arguments. He said that the existence of God is not self-evident because "no one can mentally admit the opposite of what is self-evident; . . . but . . . the fool said in his heart there is no God. Therefore, that God exists is not self-evident." He continues: "A thing can be self-evident in either of two ways; on the one hand, self-evident in itself, though not to us; on the other, self-evident in itself and to us. . . . If . . . there are some to whom the essence of the predicate and subject is unknown, the proposition will be self-evident in itself, but not to those who do not know the meaning of the predicate and sub-

ject of the proposition. . . . I say that this proposition, 'God exists,' of itself is self-evident, for the predicate is the same as the subject, . . . Now because we do not know the essence of God, the proposition is not self-evident to us; but needs to be demonstrated by things that are more known to us, though less known in their nature—namely, by effects."

It is interesting to see what sort of arguments Thomas chooses. He says: "I answer that, the existence of God can be proved in five ways.

"The first and more manifest way is the argument from motion. It is certain, and evident to our senses, that in the world some things are in motion. Now whatever is in motion, is put in motion by another, for nothing can be in motion except it is in potentiality to that towards which it is in motion; whereas a thing moves inasmuch as it is in act. For motion is nothing else than the reduction of something from potentiality to actuality. But nothing can be reduced from potentiality to actuality, except by something in a state of actuality. Thus that which is actually hot, as fire, makes wood, which is potentially hot, to be actually hot, and thereby moves and changes it. Now it is not possible that the same thing should be at once in actuality and potentiality in the same respect, but only in different respects. For what is actually hot cannot simultaneously be potentially hot; but it is simultaneously potentially cold. It is therefore impossible that in the same respect and in the same way a thing should be both mover and moved, that is, that it should move itself. Therefore, whatever is in motion must be put in motion by another. If that by which it is put in motion be itself put in motion, then this also must needs be put in motion by another, and that by another again. But this cannot go on to infinity, because then there would be no first mover, and, consequently, no other mover; seeing that subsequent movers move only inasmuch as they are put in motion by the first mover; as the staff moves only because it is put in motion by the hand. Therefore it is necessary to arrive at a

first mover, put in motion by no other; and this everyone understands to be God."

Thomas does not appeal to religious feeling, but to the phenomena of mechanics.

He derives his second proof from the observation that there is an order of efficient causes in the world of sense. This order cannot regress to infinity, so there must be a first efficient cause, which is God.

The third is derived from possibility and necessity. "That which does not exist only begins to exist by something already existing. . . . Therefore we cannot but postulate the existence of some being having of itself its own necessity, and not receiving it from another, but rather causing in others their necessity." This being is God.

In the fourth, God is deduced as "the maximum in any genus" which is "the cause of all in that genus; as fire, which is the maximum of heat, is the cause of all hot things."

In the fifth, the existence of God is deduced from the evidence of design in the government of the world.

While he proves the existence of God by reason, he denies that it is possible to attain to knowledge of the Trinity by reason.

He opposes Richard of St. Victor's assertion: "I believe without doubt that probable and even necessary arguments can be found for any explanation of the truth."

In his reply, he says: "Reason may be employed in two ways to establish a point: firstly, for the purpose of furnishing sufficient proof of some principle, as in natural science, where sufficient proof can be brought to show that the movement of the heavens is always of uniform velocity. Reason is employed in another way, not as furnishing a sufficient proof of a principle, by showing the congruity of its results, as in astrology the theory of eccentrics and epicycles is considered as established, because thereby the sensible appearances of the heavenly movements can be explained; not, however, as if this proof

were sufficient, forasmuch as some other theory might explain them. In the first way we can prove that God is one; and the like. In the second way, reasons avail to prove the Trinity; as, when assumed to be true, such reasons confirm it. We must not, however, think that the Trinity of persons is adequately proved by such reasons. . . ."

This passage exhibits again Thomas' predilection for scientific ideas, and shows that he had an intellectually correct understanding of the nature of a scientific theory. It follows that the slow development of experimental science in his time was due not to lack of intellectual comprehension of the nature of scientific method, but to the failure of contemporary society to provide a strong motive to use the method.

Thomas devotes a part of the *Summa* to a *Treatise on Man.* He discusses the nature of ideas and of matter, and how the mind acquires knowledge of matter. When this has been done, it is possible to determine whether science gives real or illusory knowledge.

He asks "whether the soul knows bodies through the intellect," and replies: "Science is in the intellect. If, therefore, the intellect does not know bodies, it follows that there is no science of bodies; and thus perishes natural science, which treats of mobile bodies."

He would have had no patience with modern writers who doubt the existence of the external world and the ability of science to give real knowledge of it.

He then criticizes Plato's theory of ideas, and Democritus' theory of the discharge of images, as respectively extreme idealist and materialist conceptions of the mode of knowing.

Plato maintained that ideas are immaterial and separate, and that the soul does not understand corporeal things, but separate ideas therefrom.

Thomas contended that this was false because ideas are immaterial and immovable, and "knowledge of movement and matter would be excluded from science (which knowledge is

proper to natural science), and likewise all demonstration through moving and material causes. Secondly, because it seems ridiculous, when we seek for knowledge of things which are to us manifest, to introduce other beings, which cannot be the substance of those others, since they differ from them essentially. . . . Now it seems that Plato strayed from the truth because, having observed that all knowledge takes place through some kind of similitude, he thought that the form of the thing known must of necessity be in the knower in the same manner as in the thing known. Then he observed that the form of the thing understood is in the intellect under conditions of universality, immateriality, and immobility: which is apparent from the very operation of the intellect. . . . Wherefrom he concluded that the things which we understand must have in themselves an existence under the same conditions of immateriality and immobility. . . . But there is no necessity in this. For even in sensible things it is to be observed that the form is otherwise in one sensible than in another: for instance, whiteness may be of great intensity in one, and of a less intensity in another. . . .

"The intellect which abstracts the species not only from matter, but also from the individuating conditions of matter has more perfect knowledge than the senses, which receive the form of the thing known, without matter indeed, but subject to material conditions."

He then discusses Democritus' theory, that knowledge is caused by a discharge of images from the object into the human sense organs, and mentions that when Democritus proposed this theory, philosophers had not yet begun to distinguish between intellect and sense.

Plato held that intellectual knowledge did not proceed from sensible knowledge, and that sensible knowledge did not proceed to sensible things, but "these rouse the sensible soul to the sentient act; while the senses rouse the intellect to the act of understanding."

But, says Thomas, "Aristotle chose a middle course. For with Plato he agreed that intellect and sense are different. But he held that the sense has not its proper operation without the cooperation of the body; so that to feel is not an act of the soul alone, but of the *composite*. And he held the same in regard to all the operations of the sensible part. Since, therefore, it is not unreasonable that the sensible objects are outside, the soul should produce some effect in the *composite*. Aristotle agreed with Democritus in this, that the operations of the sensitive part are caused by the impression of the sensible on the sense; not by a discharge, as Democritus said, but by some kind of operation."

According to Aristotle, the impression caused by the sensible does not suffice, but something more noble is required, and this is the active intellect.

In the intellectual part, there is something active and something passive.

Thomas' philosophy is deeply influenced by the later and scientific works of Aristotle. The tone of his argument does not seem religious to many readers. He was trying to base Christian philosophy on Aristotle, "the least religious of the great philosophers." He rejected Anselm's proof of the existence of God, and proofs of the eternity of the world. He adopted the idea of "potential" from Aristotle, which seems important in the theory of growth and embryological development. A. E. Taylor believes that Aristotle may have obtained the theory of potential from Plato, who writes in the *Theaetetus:* "In a sense we have none of these pieces of knowledge when we are not using them; what we have is the power."

Taylor considers that any theory of perception that will meet the needs of science must resemble Thomas'.

It will have to combine, he thinks, as Thomas meant to combine, "the two complementary positions that our knowledge of the world around our bodies is mediated in fact by highly complicated processes of a very special kind, and that *as knowledge*

it is *direct, unmediated* apprehension not of 'ideas' or 'images' but of actual physical reality."

But in spite of Thomas' critical realism and distrust of speculation without solid root in empirical fact, Taylor considers his philosophy more Platonic than Aristotelian.

Thomas' attempts to reconcile Aristotle's doctrine of the eternity of the universe and the mortality of the soul with Christian dogma do not seem to be very successful. He could not see any flaw in Aristotle's theory of the universe, so he accepted the Christian dogma of the creation of the universe in time by an act of faith.

Aristotle taught that soul and body are one substance, and that the soul is the form of the substance of the body. When form and matter are dissolved at death, the individual is destroyed forever. Thomas tried to evade this conclusion by the supposition that the soul is a "separable form." This appears to conflict with Aristotle's theory, and with his own teaching that the universal can only be "individualized" in matter. Aristotle's doctrines of the eternity of matter and the unity of the intellect, which denied individual immortality, were developed by the Spanish Muslim commentator Averroes, who lived from 1126 until 1198. Thomas made a severe attack on Averroes, but the latter, with his tradition of Muslim science and medicine, approached nearer to the naturalistic core of Aristotle's later philosophy.

According to Averroes, matter is eternal and the theory of a creation is impossible. The universe consists of a hierarchy of principles connected in a transcendental unity. One of these is the Active Intellect. This manifests itself continuously in the form of collective human consciousness and is immortal. The human soul is a fragment of the Active Intellect temporarily detached to animate the body, and after death it rejoins its source.

The soul has no independent existence in immortality and

cannot have experiences analogous to those which occur during life. It cannot remember or feel, and is not susceptible to reward or punishment.

This theory was denounced by Muslim fanatics and was incompatible with the Christian belief in heaven and hell. Its holders were indifferent to religious formulae, but Averroes had to protect himself by affirming that the received religions are excellent instruments of morality, and that those who incite scepticism in the people, or demean God before the vulgar, are heretics. But "the special religion of philosophers is to study what exists, for the most sublime worship of God is the contemplation of his works, which leads us to a knowledge of him in all his reality."

Averroism was encouraged by Frederick II, the patron of Michael Scot, who came to Sicily from Toledo with translations of Averroes and the later works of Aristotle.

The brilliant Moorish culture which had reared Averroes in Spain at the end of the twelfth century was soon repressed by Muslim conservatism. But Averroes troubled the Christian theologians for centuries after his influence in Islam had declined.

Some enthusiastic Thomists believe that Thomas' onslaught on Averroes saved Christianity from intellectual conquest by Islam, and that his victory was even more crucial than that of Charles Martel at Poitiers. This view seems incompatible with the transience of Averroes' influence in Islam.

Only a small fraction of Thomas' writings were concerned with nature and natural science. There are long discussions as to whether men are assailed by the demons, whether there are orders among the demons, whether among the demons there is precedence, whether the mother of God was a virgin, and whether the fire of the final conflagration is of the same sort as our fire, etc.

Thomas says that "good can exist without evil, whereas evil

cannot exist without good; so there is order in the demons, as possessing a good nature." (They are wicked by their own free will.)

"The demons are not equal in nature; and so among them there exists a natural precedence; which is not the case with men, who are naturally equal."

The Christian doctrine of human equality has had profound influence on the restitution of the dignity of human labour, and this indirectly on experimental science. Thomas' order, the Dominicans, were more democratic than the Benedictines, for their abbots were elected for three years only, while the Benedictine abbots were elected for life. The Franciscans and the Dominicans were supported with special favour by the new bourgeoisie.

"Joseph is called the father of the Saviour, not that he really was His father, as the Photinians pretended, but that he was considered by men to be so, for the safeguarding of Mary's good name."

Thomas' system was submitted to detailed criticism by many successors, among whom Duns Scotus was the most brilliant. He was born in 1285 and died at the early age of forty-three. He transferred one doctrine after another in Thomas' system from the province of reason to the province of faith and, as Harris says, the psychological effect was enormous. "The pre-established harmony between reason and revelation, which was the fundamental postulate of medieval thought," collapsed with alarming rapidity.

Some believe that Thomas provided the durable basis for all subsequent theology and science. Others believe that his patient, comprehensive and lucid exposition of the natures of Christian dogma and scientific thought left their incompatibility obvious and undeniable.

Some of the modern followers of St. Thomas would like to see a revival of his ordered system of the universe. They dwell on his distinction between persons and individuals and

attack liberal society as a collocation of individuals in contrast with St. Thomas' society of persons, and are prepared to go far in attempts to form such a society.

Etienne Gilson writes: "The so-called Liberalism of the previous generation was but a flattering name for that monster: a human society, not of persons, but of individuals. Against such a Liberalism the brutal reaction of the so-called 'Totalitarian State' was, if not justified, at least almost necessarily required."

When the followers of St. Thomas express opinions of this sort, it is as well to recollect their master's long disquisitions on demons and his frequent inability to recognize the intimations of common sense, besides his bold and subtle attempts to find material foundations for religious belief.

43

ROGER BACON AND MEDIEVAL EXPERIMENTAL SCIENCE

Thomas Aquinas understood the logic of scientific method, but he did not appreciate the weight of the experimental part of it. He believed that the truth of a theory should be tested by an appeal to experience, but he did not feel that experience should be systematically explored by manual means in order to supply data for new theories. His attitude towards experience was passive and negative, and he did not advocate the positive extension of experience by artificial means.

The importance of the positive experimental part of science was emphasized by his rival Roger Bacon, who lived from 1214 until 1292. Roger Bacon has been celebrated recently as the first modern scientist, and an isolated genius centuries in advance of his time. His works contain many startling passages, and when these are separated from their context, and from the general scientific knowledge of his time, they seem uniquely modern in a medieval scientist. He said: "The most useful, the greatest, and most beautiful lessons of knowledge, as well as the secrets of all science and art, are unknown." He quoted with approval Seneca's forecast of the future achievements of science and his view that he contributed most to discovery who hoped that it could be made. He believed: "Machines for navigation can be made without rowers so that the largest ships on rivers or seas will be moved by a single man in charge with greater velocity than if they were full of men. Also cars can be made so that without animals they will move with unbelievable rapidity; such as we opine were the scythe-bearing chariots with which the men of old fought. Also fly-

ing machines can be constructed so that a man sits in the midst of the machine revolving some engine by which artificial wings are made to beat the air like a flying bird." He visualizes the invention of small machines for raising and pulling great weights, and machines "for walking in the sea and rivers, even to the bottom without danger."

Bacon made considerable contributions to optics, but none of them was perfected. He followed the works of Alhazen, and made experimental and theoretical investigations to improve the knowledge of the laws of refraction and reflection. He attempted to apply this knowledge to the improvement of aids to human vision. He made experiments with plano-convex lenses, and noted that if letters are viewed through a lens "shaped like the lesser segment of a sphere, with the convex side towards the eye, and the eye being in the air, he will see the letters far better, and they will seem larger to him. For this reason such an instrument is useful to old persons and to those with weak eyes, for they can see any letter, however small, if magnified enough." He understood that the rays from the object were refracted at the curved surface of the lens, but he did not know that they were also refracted at the plane surface. He explains that magnification is due to the angle subtended at the eye by the image being larger than that subtended by the object. "It is on the size of angle on which this kind of vision depends, and it is independent of distance . . . so a boy can appear a giant . . . a small army might seem very large, and though far away appear near, and conversely: so, too, we could make sun, moon, and stars apparently descend here below." He suggests that "glasses can be constructed so that objects at a very great distance appear to be quite close at hand and conversely." This appears to be the telescope without glasses. "The heavens might be portrayed in all their length and breadth on a corporeal figure moving with their diurnal motion, and this would be worth a whole kingdom to a wise man."

Bacon belonged to a rich family and probably earned considerable fees while lecturing in Paris between 1236 and 1251. He spent two thousand livres (or ten thousand pounds in modern money) on the purchase of books, experiments and instruments, journeys to meet scholars, and secretaries. He worked for three years on the construction of a concave burning mirror and spent five hundred pounds on the research. He recorded how the craftsmen who made the mirrors became quicker and more economical with increasing experience. He considered that the ideal student "makes no account of speeches and wordy conflicts but follows up the works of wisdom and remains there. He knows natural science by experiment, and medicaments and alchemy and all things in the heavens or beneath them, and he would be ashamed if any layman, or old woman or rustic, or soldier should know anything about the soil that he was ignorant of. Whence he is conversant with the casting of metals and the working of gold, silver, and other metals and all minerals; he knows all about soldiering and arms and hunting; he has examined agriculture and land surveying and farming; he has further considered old wives' magic and fortune-telling and the charms of them and of all magicians, and the tricks and illusions of jugglers. But as honour and rewards would hinder him from the greatness of his experimental work he scorns them." He remarks that he has "learned more useful and excellent things without comparison from very plain people unknown to fame in letters, than from all [his] famous teachers." He investigated séances and said that "when inanimate objects are quickly moved about in the darkness of morning or evening twilight, there is no truth therein but downright cheating and cozenage."

He was the first European to give a description of the composition and preparation of gunpowder. His account of the geography of Europe, Asia and Africa, and the size and sphericity of the earth, was quoted by Pierre d'Ailly in his *Imago Mundi*, which was published in 1487, and probably encouraged

Columbus to attempt to reach the Indies by sailing westwards.

Bacon was commanded by the Pope in 1266 to send him copies of all his works. He compiled his *Opus Majus* to satisfy this order. It is arranged in seven parts. He discusses the causes of human error in the first part, and ascribes it to undue regard for authority, habit, popular prejudice and false conceit of knowledge. In the second part he explains the value of philosophy to theology. In the third he discusses the study of foreign languages, and shows that each should have its own grammar, and that the meaning of literature cannot be correctly apprehended without scientific methods of textual criticism. In the fourth he describes mathematics as the key to all other sciences, especially astronomy, optics, theology, chronology, astrology and the correction of the calendar, and outlines contemporary geography. The fifth deals with optics, and the sixth with experimental science. The final section is devoted to morals, and the relation and duty of man to God. It contains the first comparative study of religions and a proof of the superiority of Christianity.

A summary of Bacon's achievements makes a profound impression, and is the source of the tendency to exaggerate them. Thorndike has made a salutary criticism of excessive claims for him.

When Bacon's works are carefully examined it is seen that his theological motives are just as strong as those of Thomas Aquinas and the other scholastics. He firmly believes in astrology and asserts that "it is manifest to everyone that the celestial bodies are the causes of generation and corruption in all inferior things."

None of his lines of experimental work were entirely original. The inspirations may be found in Alhazen, Albertus Magnus, Grosseteste, Abélard and others. He did not make any of the great medieval inventions, such as chimney flues and window panes, the rudder and the mariner's compass, Arabic numerals, paper, lenses and spectacles, and gunpowder. Thorndike

doubts the tradition that he was persecuted and imprisoned for many years by ecclesiastical superiors who disapproved of his scientific researches. The Franciscans, to whom he belonged, included many eminent members who had contributed to experimental science, such as Grosseteste.

A reading of Bacon's works suggests that his questioning of authority had two motives: a personal motive due to rivalry and jealousy of scholars such as Albertus Magnus, whose ecclesiastical careers had been far more successful, and an impersonal motive due to a better appreciation of the importance of experiment, as compared with logic, in the advancement of science. Bacon mixes brilliant comment on scientific methods with penetrating criticisms of the personalities of rivals. This tactlessness would have damaged his career in any organization in any age.

Bacon did not turn any of his researches to practical use, so he was not convincing to the purely practical man. He had not provided his order with any new process for making money.

Nevertheless, the personal failure of his career was significant. His conception of scientific method, if not perfect, was advanced. His statements show that he was conscious that the study of the processes of handicraft was essential to the development of experimental science. His plan of an encyclopedia and his *Opus Majus* show that even if he had not escaped from the integument of theology, he aimed at the creation of an expanding body of science within it. He may not have realized that ultimately this would break out and pursue an independent life.

In Bacon's scientific work there is a combination of logic, cultivated by the Church and the governing classes, with the technique of the craftsman and the independence of the bourgeois. His failure may be interpreted as due not only to temperamental tactlessness, but to a combination of class cultures in advance of its time. Indeed, his tactlessness may not have been temperamental, but acquired through struggles with cultural

conservatism. Bacon, like Boyle, was a pious man who consorted with mechanics, and made experiments. He died in obloquy, while Boyle was universally respected. Does not this suggest that in Bacon's day the combination of logic with technique, and the knowledges of a governing class and a manual class, was not yet reputable, while in Boyle's day it had achieved repute?

44

THE GROWTH OF UNIVERSITIES

The chief feature of a university is the granting of degrees to students who obey its rules of residence and pass its examinations. The Greek schools, such as the Academy and the Museum, and their Roman imitations, and the monastic schools, which alone preserved learning from the sixth until the tenth century, did not grant degrees and require precise periods of residence. The formalization of higher education in the shape of university teaching was a medieval invention and occurred in the twelfth century.

The growth of Norman feudalism and the first efforts of the new bourgeoisie increased social prosperity in the eleventh century, and created a demand for clerks who could assist in administration. When this occurred, education was entirely controlled by monasteries, and the first effect was to increase the number of students at monastic schools. But the new demand was for clerks who could assist in secular affairs rather than for monks learned in the nature of the soul. The conduct of education tended to pass from monks to secular clergy less exclusively concerned with pure religion. The teaching in the cathedral schools was more secular than in the monasteries because the cathedral was the centre of a growing town and in closer contact with secular interests. Rashdall sees in the transfer of educational activity from the monks to the secular clergy in the eleventh century the great educational revolution which contains the germ of the university movement.

The new teachers in the cathedral schools supplied a need and attracted increasing numbers of students. At first, the

students followed the teacher as he moved from school to school, but presently the numbers became too large for continuous migration. The teachers tended to settle in cathedral towns, which were the only centres that could supply board and lodging for large numbers of visiting students. At this stage, the cathedral schools of Bec, Tours, Chartres and Rheims became famous. Shortly afterwards they were challenged by the cathedral school in Paris. The French monarchy was losing its nomadic character and beginning to settle in Paris as its capital. This stimulated trade and attracted personalities, and the growing city could support a large number of students better than its competitors. The superiority of the Paris school was confirmed by the brilliant teaching of Abélard.

The students who lodged in the neighbourhood of famous teachers were not at first organized. They were individuals in a much larger local population and their activities did not impinge on local life. But when the numbers grew into thousands, new social problems arose. The teachers could not know all their students intimately, and personal recommendation from a teacher was no longer a sufficient qualification. The increasing number of students stimulated intellectual competition and a demand for an objective system of measuring knowledge, and it created a new social class. Nearly all of the students and teachers in Paris were strangers, and they did not take part in the productive work of the city. Their interests differed from, and often came in conflict with, those of the townsmen, or bourgeoisie. The students formed associations like those of craftsmen to protect their educational and social interests. The craftsmen named their associations "universities" or "guilds," and the students appropriated the name "university" from them. The application of "university" was gradually narrowed to denote societies of masters and scholars, and there might be several "universities" of medical or law students in the same town. The "universities" were governed by guild regulations of the usual type. The student could not earn a living by teach-

ing until his guild had awarded him a master's degree. This was a teacher's certificate. It was awarded by examination, to prevent favouritism and monopoly. The possession of the master's degree was a proof of competence to teach. In Paris the additional licence to teach was granted by the chancellor of the cathedral.

The educational needs of the students prompted them to organize their new system of teaching and examination. The clash of their interests with the townsmen's prompted them to seek social privileges for their guilds or universities. The chief legal enactments which established their privileges occurred after town-and-gown rows, which were class conflicts between the bourgeoisie and the students. After serious fighting between these parties, Philip Augustus laid down in 1200 that Paris students should be exempted from the justice of lay courts. Oxford's first privileges were granted in 1209, after a riot between bourgeoisie and students, when hundreds of students had to leave the city. They went to Cambridge, where they founded a new centre of learning.

The number of students in the new universities was relatively very large. Paris may have contained seven thousand students when her total population was between twenty-five and fifty thousand. This was a fraction of about one in five. Today the fraction is about one in five hundred. The medieval student population was a formidable social class, and the ability of medieval society to support such a vast proportion of students is a proof of its vigour. The proportion at prewar Oxford is about one in twenty.

Educational institutions with organized teaching and examinations and a privileged social position had appeared in the twelfth century at Salerno, Bologna, Paris, Montpellier and Oxford. The word "university" was first applied to the Paris institution in 1208. The first college for the accommodation of students was founded there about 1180.

The nature of some of the conflicts between bourgeoisie and

students is seen in the disputes in Bologna over the prices of books, board and lodging. The students' guild forced the prices down by threatening to leave the city, and professors were made to lecture agreeably by threats to withhold their fee.

Universities tended to specialize in training for particular professions. Salerno specialized in medicine, probably owing to its proximity to Islam. Bologna specialized in law. It was at the crossroads of northern Italy, and important railway junctions are now there. Paris specialized in theology and dialectic. This was connected with the growth of the strength of the French monarchy, which attracted alliance with the popes. The French capital became the cultural centre of the Church, which produced the bias in theology, and as the centre of government it stimulated interest in dialectic, which is of professional value to prospective Cabinet ministers who wish to defeat their competitors in discussions on policy and secure the king's approval. Aristotle's books on natural science were prohibited in Paris in 1215. This shows the bias of the authorities. The prohibition was virtually ignored. The organization of teaching created textbooks and orderly argument. This was accompanied by the perfection of a lucid and precise medieval Latin modelled on French. This contributed much to the clarity of thought which subsequently assisted scientists to define the principles of modern science.

The lectures consisted largely of comments on texts. Students made elaborate notes, and the subjects were debated. The memory of these wrangling debates is preserved in the title given to the most successful candidates in the Cambridge mathematical examinations. The lectures were delivered in the teacher's dwelling or in a hired hall. Alexander Neckam, whose mother was the foster-mother of Richard Cœur de Lion and who was suckled at the same time as Richard, recorded that in 1200 the textbooks in use included the new logic, science and metaphysics of Aristotle, Boethius on arithmetic and music, Euclid and the Latin translation of the Arabic commentaries

on Ptolemy, Galen and Hippocrates. Avicenna had not yet been introduced. Complaints that students neglected classics for professional studies had already begun. The medieval student, especially at Paris, was trained for executive work in church and state. He looked to the rulers for employment and adopted their social perspective. He was a stranger in the city of his university and he received his allowance from elsewhere. He determined his own hours of study, and appeared to the local bourgeoisie as a member of the leisured class, as well as an ally and dependent of the rulers. The universities owed their legal existence to resistance against the bourgeoisie, and yet the bourgeoisie provided the conditions under which they came into existence.

Rashdall is unable to find any explanation of the establishment of a university at Oxford other than ease of access and commercial prosperity. He writes: "To its position, too, must be ascribed the rapid increase in the commercial importance of Oxford after the final cessation of Danish devastations and especially after the beginning of the twelfth century. Its early selection by Jews as a business centre marks this development. In short: Oxford must be content to accept its academic position as an accident of its convenient situation . . . only one of the largest towns in the kingdom would be equal to the housing and feeding of many hundreds or thousands of strangers."

While the bourgeoisie simultaneously supported and opposed the universities, it frequently sent its sons there, to pass from its own class into those of leisure and government. Sons of peasants achieved the same social transference. They earned a living by tutoring until they had graduated. The influence of social transference is shown in the development of the mode of conferment of degrees in some universities. It grew more like the bestowal of knighthood than admission to a craftsmen's guild.

The university, which was invented eight centuries ago, still retains its effectiveness as an instrument of social transference, and education for the retention of power. But it is not

even yet a perfect instrument for the advancement of science. The universities were progressive in science during the twelfth century. They spread the new knowledge of Greek and Muslim science. When this had been accomplished, they were able to make many more contributions, owing to their social perspective. They aimed at transference of manual workers into the literary class, so their atmosphere was antagonistic to manual work, and therefore to experiment. The success of Aquinas and the failure of Roger Bacon is partially explained by these circumstances.

After the assimilation of Greek and Muslim science, which was transmitted to Western Europe in books, the universities obstructed rather than assisted the direct development of science. The study of astronomy, alchemy and experimental science was restricted to small groups in Pisa, Marseilles, London, and the other centres of navigation and foreign trade.

The culture of the universities was aristocratic, and most of their leaders were rich men. Abélard was the son of a feudal lord, Bacon was well-to-do, and Aquinas was of royal descent. But Abélard's vulgar inquisitiveness, Bacon's interest in crafts, and Aquinas' pedestrian arguments, with their homely material illustrations, rose as much from the social energy created by the bourgeoisie as from the vigor of the Norman knights.

The rapid intellectual development slowed down in the fourteenth century. After the scholars at the universities had assimilated earlier science, they could not advance rapidly, as they did not include experimental work in their system.

The lack of new material for study due to the poverty of experimental research sterilized the intellect. In addition, the resources of Western Europe were wasted in the struggle for mastery between France and England, which started at the end of the thirteenth century and lasted for a hundred years. If this disastrous war had not occurred, the Turks would probably not have captured Constantinople in the fifteenth century, and Russian social development might have advanced far more

quickly. Thinkers such as William of Ockham, who died in 1349, had clearly recognized some of the theoretical principles of modern science. Ockham announced the principle of simplicity as a director of research when he asserted that "entities must not be unnecessarily multiplied." Dirac considers this principle the chief intellectual motive which guided Newton in his search for universal laws. Ockham appreciated the idea of evolution in social organizations, for he said that "no human institution is absolute or final, and neither Pope nor Emperor can claim exemption from the general law of progress and adaptation." This opinion was inspired by his part in the class conflict between church and state. He was engaged by Louis of Bavaria to provide arguments in his struggle against the papacy. Pirenne notes that the handicrafts reached their highest status in the first half of the fourteenth century. A sort of industrial Malthusianism then appeared, and the local market was surrendered to a small number of masters. He believes that this was a cause of the sudden check in urban population and the demand in the next century for the abolition of corporations and the liberty of the handicrafts. In the middle of the same century about half the population of Western Europe was killed by the Black Death.

Intellectual work declined under these conditions. Petrarch noted in the second half of the fourteenth century how the universities of Montpellier and Bologna had declined since his youth, and how the prosperity, trade, tranquillity and order of those cities had disappeared. Thorndike has commented on the decline of handwriting and prose style in the fourteenth and fifteenth centuries.

The perfected methods of criticism were applied with success in the fourteenth century to the theory of mechanics. Duhem's exposition of the medieval discovery of the principle of virtual work has been mentioned. Buridan and Albert of Saxony gave a correct theory of impetus in the second half of the fourteenth century. Buridan held that the celestial bodies

must obey the same laws as terrestrial bodies. The conditions were prepared for Newton's flight of imagination, by which he saw that the moon should obey the same laws as terrestrial projectiles. Buridan defined mass in terms which foreshadowed Newton's. Albert of Saxony suggested that the motion of a heavy falling body was uniformly accelerated. He discussed the movement of the sun, and the influence of erosion in shaping the geological features of the earth.

Nicolas of Oresmi suggested in the fourteenth century the use of coordinates, and was apparently the first to use fractional exponents in algebra. The Black Death inspired Henry of Hesse, who lived from 1325 to 1397, to suggest the possibility of new species of organisms. He forecast that new diseases would appear, and new species of herbs for their cure. He conceived the possibility of gases other than air before von Helmont, for he said that water exhalations are aqueous, while those from earth are earth vapour, and those from flesh, flesh vapour. The alchemists had conceived the nature of gases, and the problems of their density and rarefication were discussed scholastically. Petrus Bonus contended that "in spirits there are bodies potentially, and in bodies spirits exist." In mercury the volatile state was foremost, while in gold it was concealed.

Various theories of attraction and gravitation were proposed in the fourteenth and fifteenth centuries to explain the relation between the moon and tides and the suspension of the earth in space. The measurement of small fractions of time was conceived on paper, and records of comets, earthquakes and weather were kept.

Nicolas of Cusa, who lived from 1401 to 1464, suggested timing the fall of bodies with corrections for the effect of resistance by the air. He advocated the use of the balance in chemical investigations, and suggested, two centuries before Hales, that the relations between the weights of a seed and the grown plant, and the weights of earth before and after growth, and the weight of ash obtainable from the plant might be worth

investigation. But he did not make the experiment. He believed that qualities could be distinguished by weighing, and measured the humidity of the air by weighing balls of absorbent material.

Henry of Hesse in the previous century experimented with surface tension.

Thorndike mentions that much attention was devoted at this period to reform of the calendar and the compilation of astronomical tables. He complains that printing is the only medieval invention that has been adequately studied. The mariner's compass and gunpowder were introduced in the twelfth century. Nearly all of the British coalfields were being worked in 1300, and the rudder was introduced at about that date. Thorndike considers that "the mechanical clock of the early fourteenth century was in a way the parent of all subsequent machinery."

Ptolemy's *Geography* was translated in 1409. Like the translations of Archimedes, its effects were not entirely fortunate. The early navigators were misled by it, and medieval geographical discoveries were neglected. Medicine may have learned something from the Black Death. It may have gained a better understanding of the nature of infection. Leprosy largely disappeared in and after the fourteenth century. Henry of Mondeville practised antiseptic surgery at the beginning of the fourteenth century. The mercury treatment for syphilis was introduced in the fifteenth century, and remarkable operations in plastic surgery were performed. Thorndike quotes Fagio's description of the Brancas' operations on the nose, which was published in 1456. The elder Branca "thought out a way to re-form and complete dissected and mutilated noses." He cut skin from the face of the mutilated person and repaired the nose with it. His son improved the operation, and took the skin "from the arm, so that no facial deformity resulted therefrom. And he inserted the remains of the mutilated nose, and bound them up so tightly that the mutilated person could not

even move his head. After fifteen or sometimes twenty days, he would little by little cut open the bit of flesh which adhered to the nose and re-form it into nostrils with such skill that the eye could scarcely detect where it had been joined on, and all facial deformity was completely removed."

These brilliant contributions were not sufficient to sustain the pace of enquiry that had been set in the twelfth century. In the thirteenth century the authorities had become generally alarmed. As enquiry spread, heresy multiplied. Many heretics were lynched by the populace between 1020 and 1150. After that time, an increasing number were condemned by prelates. The Church completed in 1233 the formal organization of the Inquisition as an instrument for the extermination of heresy. Twenty years later, Aquinas showed how a logically impeccable justification of execution for heresy could be deduced from the church dogma. If Aquinas had proposed one hundred years later arguments as original as some he had suggested in 1250, he would have found himself in danger of the stake. But this original thinker had died young, and his works had been sanctified before their novelties had been disapproved. The Inquisition, like modern Fascism, surprised some of its early supporters in their later years by striking at the innovations of conservatives as well as radicals.

45

THE INQUISITION

The survival of the Church through the dark centuries following the disintegration of the Roman Empire gave it unique power. It became the framework of Western European society, and its power grew during the centuries of primitive feudalism. In those times few had the leisure or training to think about its dogmas, as nearly all were absorbed in the anxious labour of obtaining a bare living. Coulton remarks that in the seventy-three years from 987 to 1059 there were forty-eight years of famine in northern France, and at least two of these were marked by cannibalism.

The improvement of conditions which began in the tenth century, and was associated with the growth of the towns and the bourgeoisie, provided new quantities of social energy, which throbbed through all the arteries of the social organism. A large part of the new urban wealth was poured into the Church, and a new vigour from the same source permeated religious thought. Dogmas which had acquired immense prestige through centuries of negative acceptance now became the object of positive faith. The new energy at first sought for expression through accepted ideas. It seized the old dogmas and believed in them with a new force. At the same time society was becoming more complicated through its new developments. The travelling traders and the bourgeoisie were beginning to fill the orthodox modes of their thought with a new content inspired by their interests. Crusaders acquired some knowledge in the East of other religions. Through influences such as these, men began unconsciously to derive their own interpretations of the ancient dogmas.

The increasing vigour of thought made men more conscious of the evils of contemporary society. This created the illusion that society was growing worse, though in fact it was improving. The new energy of the leaders of the Church at first expressed itself in an increase of passionate faith. They accepted the old dogmas more enthusiastically than ever, with a new determination to make them work.

But the same social development which had provided their own energy also produced a proliferation of divergent religious ideas. The world seemed to the new leaders to be racing towards damnation, and they felt called at the last moment to save it. If they did not do their best, they would be eternally damned themselves.

Pope Innocent III issued a decree in 1199 ordering clergy, magistrates and people to destroy heresy. He wrote: "The decay of a century tottering to old age may be scented in the corruption not only of the elements, but even in that most worthy of all creatures, fashioned in the image and likeness of God, and set above the fowls of the air and all the beasts of the field in privilege of dignity; nor does he merely fail in these days with the failing century, but he also infects and is infected with the foul canker of old age. For man, most unetched, sinneth at the last; and he who, at his own creation and that of the world, could not remain in Paradise, is now degenerating in these days of dissolution for himself and the whole earth; and, at the end of time (forgetting the price of his redemption, by trusting himself into the manifold vain meshes of questioning), entangles himself in the snares of his own fraud, and falls into the pit which he hath digged. . . . Heresies swarm, and the heretic, robbing his brother of his heavenly inheritance, makes him heir to his own heresy and to damnation."

Innocent III gave expression to the current intense belief in the reality of heaven and hell, and to the necessity for eternal salvation by faith. In the view of those who held this belief, a heretic committed treason against God. He damned himself to

eternal torment and endangered the eternal happiness of all whom he met or influenced. Aquinas argued that if a man may be justly executed for treason against kings, how much more justly may he be slain for treason against God!

Any method of suppressing heresy could be justified by this belief, because no punishment that could be inflicted in finite earthly life was commensurable with that suffered eternally in hell. In the heretic's own interest, the most extreme earthly torture was infinitely justified if it brought him to repentance and eternal salvation. If it did not, then he should be despatched to hell by execution as quickly as possible, to prevent him from corrupting the faithful.

Lucius III had created an episcopal inquisition in 1184 when he ordered bishops to make the most thorough enquiries into heresy in their dioceses. The civil authorities were ordered to punish heretics discovered by these enquiries, under the pain of deposition, confiscation and excommunication. This decree was found insufficient, and Gregory IX began to send inquisitors from Rome to supervise the local investigations. The inquisitors were chosen from the new and enthusiastic Franciscan and Dominican friars, whose orders were founded in 1209 and 1216, respectively. They were directed from a central office at Rome, under the Pope's control, and rapidly evolved a system for conducting their enquiries. The old Roman Imperial law had recently been rediscovered and its procedure, and permission of torture, were adopted. The Inquisition assumed that any man accused of heresy was guilty until his innocence was proved. This was contrary to the old Germanic law which has survived in England and some other countries, and which assumes the accused is innocent until his guilt is proved. Its judges were ecclesiastical. Their procedure was secret and withheld from the civil authorities. Witnesses were concealed, and could not be cross-examined by the accused, so prosecutions became based mainly on the stories of informers, spies and provocative agents. The testimony of criminals, which was

not accepted in other courts, was acceptable to the Inquisition. Infants could be heard, even against their parents. But neither criminals nor infants were allowed to give evidence for the defence. The accused could nominally be defended by advocates, but as the defence of a heretic was a crime, advocates could not be found. Witnesses could be tortured, so few volunteered evidence for the defence. Torture could not be legally repeated, but this law was evaded by applying portions of one torture at intervals.

The inquisitor with these devices at his disposal very rarely failed to secure a conviction.

When the machinery of the Inquisition had become thoroughly established, confessions could frequently be obtained by the threat of prosecution without any trial or torture, as the rareness of acquittal was notorious. A man needed fanatical resolution to withstand its pressure. And yet many died rather than recant. These were drawn from unorthodox religious sects. The Catharians, who flourished in the south of France, had a horror of making oaths, eating flesh, and cohabiting with their wives. They believed in the Manichaean religion, which is based on the duality of good and evil, and is incompatible with Roman Christianity. It contained ideas drawn from Persia, and other parts of the Orient, and its dissemination in West Europe was assisted by the revival of communications.

Another important heresy arose through followers of St. Francis taking their vows earnestly. These Fraticelli insisted on observing their vows of poverty and when the Pope claimed the right to overrule St. Francis' instructions, they accused him of heresy. Four of them were burned at Marseilles in 1318 as obstinate heretics.

Still more important heresies arose in the new bourgeoisie and handicraftsmen. A rich merchant of Lyons named Waldo experienced a conversion late in life. He became curious to know the true meaning of the Bible and theological works, and paid a priest to translate parts to him. When he had acquired

this knowledge he began lay preaching. The Waldensians struck at the Church's claim to control the interpretation of the Bible to the people, and were the forerunners of Protestants.

Nearly all heretics were exceptionally moral, and good citizens. As St. Bernard had observed: "If you inquire into [such a man's] faith, nothing is more Christian; if into his conversation, nothing is more blameless; and he proves by his deeds what he speaks with his mouth. . . . He cozens no man, overreaches none, does violence to none. Moreover, he is pale with fasting; he eats no bread of idleness; he works with his hands for his livelihood. Where, then, is the fox?" St. Bernard had no difficulty in finding it. "They do indeed abstain, but they abstain heretically."

It is possible to grant that the Inquisition was created by pure religious fanatics who believed they were doing their duty. But soon after the machine was created it was utilized by ambitious popes to achieve their ends in the politics of church and state, and then ambitious princes forced popes to operate it to their advantage and even against the interests of the Church.

The order of the Poor Soldiers of the Temple was organized in 1128 with the aim of protecting pilgrims. These soldiers, dedicated to obedience, poverty, and chastity, achieved great fame. Their rules were extremely strict and very secret. The Templars became a formidable order of fighting monks under the command of the Pope, and vast possessions were given to them by their medieval admirers. By 1244, they possessed nine thousand manors, and their houses, or fortresses, arose in all the centres of Christendom. The grand and secret affairs of these houses filled the populace with awe. At the beginning of the fourteenth century, the King of France, Philip the Fair, being short of money, borrowed large sums from them and they protected him from the mob when he tried to evade his financial difficulties by debasing the coinage. He arrested all the Jews in his kingdom, confiscated their property, and banished them.

Then he decided to seize the wealth of his friends the Templars. He tried to persuade the Pope to operate the Inquisition against them but did not at first succeed, so he made the Inquisitor of France act against Templars in French dominions on his own authority. All the Templars in France were arrested at dawn on a predetermined date, and their property seized. Extreme tortures were applied with haste, and a large number of confessions were collected. The Pope had to acquiesce in the imposing list and give his approval to the operation.

The chiefs of the order were made to confess first, and recommend their subordinates to imitate them. They confessed in more or less degree to initiatory rituals which included renouncing Christ, and spitting on the Cross; being kissed by the preceptor on the posteriors, navel and mouth; accepting unnatural lust as lawful; worshipping idols, and ignoring consecration of the Host in the declaration of Mass.

It is very probable that some abnormal practices occurred occasionally in a large corps of military monks, but there is no doubt that most of the confessions were false. In England where there was no Inquisition and torture was against the law, no confessions could be obtained. The Pope therefore threatened Edward II with excommunication if he did not admit the Inquisition. It was introduced for a few months, and the desired confessions were speedily obtained. The Inquisition did not reappear in England until the sixteenth century.

H. C. Lea, the great historian of the Inquisition, writing in 1887, has commented on the fate of the Templars: "Thus disappeared, virtually without a struggle, an organization which was regarded as one of the proudest, wealthiest, and most formidable in Europe. It is not too much to say that the very idea of its destruction could not have suggested itself, but for the facilities which the inquisitorial process placed in able and unscrupulous hands to accomplish any purpose of violence under the form of law. . . . It affords so perfect an illustration of the

helplessness of the victim, no matter how high-placed, when once the fatal charge of heresy was preferred against him, and was pressed through the agency of the Inquisition."

One might have thought that when the government of society could destroy heretics so easily, no one would have the courage to introduce novelties, for fear that they might prove heretical. As scientists pursue novelties by profession, they would presumably have been scrutinized particularly carefully by the Inquisition. It is therefore notable that scientists suffered relatively little under the Inquisition. Lea observes that there are few instances where the Inquisition was invoked to settle contests between free thought and authority. He suggests that this is due to the coolness of the intellect, which does not nerve the thinker "to maintain his thesis with the unfaltering resolution which enabled the peasant to approach the stake singing hymns and joyfully welcoming the flames which were to bear him to salvation." He notes that few thinkers, from Abélard and Eckhart to Galileo, were prepared to go to the stake for their intellectual beliefs. In his opinion, the only heresies which really troubled the Church were those which appealed to the emotions of the people, and appealed to the heart rather than the brain.

Lea instances Roger Bacon as a scientist who suffered under authority. Thorndike has discussed this question in some detail, and concludes that the story of Bacon's suppression is unreliable. Lea himself remarks that "its truth has been not unreasonably denied." The evidence of Bacon's style suggests that he was cantankerous besides intellectually critical. This may have been due to persecution, but it may also have been temperamental.

The monastic orders encouraged learning as enthusiastically as they supplied staffs to the Inquisition. The Dominicans produced Albertus Magnus and Aquinas, and the Franciscans, Bacon and Duns Scotus. Thorndike contends that in relation to science "the Inquisition bug-a-boo is negligible. Has any one

ever shown that the Inquisition punished a practical invention? It was not for having invented the telescope that Galileo was persecuted. Moreover, Galileo's was an exceptional case, and it cannot be shown that in the thirteenth century the Church persecuted men of science. Rather, popes and prelates were their patrons." William of Ockham and Buridan, whose contributions to scientific thought have been mentioned, were condemned by the University of Paris for heresy, but this did not do them much harm. Jean de Brescain was forbidden in 1247 to teach, owing to the condemnation of his views on matter and light as heretical. Peter of Abano and Cecco d'Ascoli were condemned for heretical astrology. The former died before his conviction was complete and the latter was burned. This cannot be accepted as an unmitigated blow to science. In the fifteenth century humanistic tolerance had spread widely. Alfonso I of Naples put the following puzzle to a preacher: "A man enclosed a consecrated Host in a vase of gold; a month later, on opening it, he found only a worm; the worm could not have been formed from the pure gold, not from the accidents which were there, without the subject; it was therefore produced from the body of Christ; but from the substance of God nothing but God can proceed, therefore the worm was God." At the same period Lorenzo Valla made corrections in the Vulgate, and had them accepted.

Lea is of the opinion that if the Reformation had not occurred, the culture of Europe would inevitably have been atheistic, or a sublimated deism. "The Reformation served a double purpose in checking this tendency to dangerous speculation. It destroyed the hard-and-fast lines of the rigid Scholastic theology, and gave to active intellects a wide field for discussion within the limits of the Christian faith." Later in the fifteenth century, Pico della Mirandola, at the age of twenty-four, "published a series of nine hundred propositions which he offered to defend in Rome against all comers, paying the expenses of those who might travel for the purpose from dis-

tant lands." These included nearly everything in theology, philosophy and science. His brilliance aroused envy, and he was accused of heresy. Pope Innocent VIII balefully remarked: "This youth wishes to end badly, and be burned some of these days, and then be infamous for ever like many another." Mirandola retired into theological studies and died at the age of thirty-two.

At the end of the sixteenth century, during the Catholic reaction against the Reformation, Giordano Bruno attacked orthodox Catholicism, and adopted the Copernican system. He was burned for heresy. But Nicolas of Cusa had argued in 1440 that the earth could not be the centre of the universe, and was made a cardinal. Both Bruno and Galileo did not manage their affairs with tact. Bruno returned to Italy after he had been condemned, and Galileo refused to live in Padua, where he would have been safe.

It is possible that the records of the damage to science done by the Inquisition are relatively meagre because science was unable to grow freely in its intimidating atmosphere. It smothered science, and therefore there were few notable scientific developments which it could strike down. But the violent disputes in the medieval schools do not reflect entirely smothered intellects. The relation between the progress of science, free thought and orthodoxy is less simple than is commonly believed. Science and the Inquisition have not always been in opposition. The discovery of America, inspired by the desire to evade the Muslim control over trade with the Indies and attack Islam in the rear, was assisted by the growth of several sciences. Columbus had been led to a more optimistic view of the ratio of land to water on the surface of the earth, and hence the possibility of reaching land quickly by sailing to the west, from Roger Bacon's revision of Ptolemy's *Geography*. He probably read a quotation of Bacon's views in Pierre d'Ailly's *Imago Mundi*, which was published in 1487. Columbus was dependent also on the great medieval inventions of the rudder and

mariner's compass, and improved methods of calculating longitude based on Muslim astronomy and trigonometry.

One other factor was equally important. This was finance. Columbus approached Henry VII of England for support, but that careful monarch would not invest money acquired by patient, honest trade in a speculative voyage. He turned to Ferdinand and Isabella, who had collected great wealth by the Inquisition. They revived the institution in northern Spain in 1480, which at the time was relatively liberal, to coerce the grandees, unify the state, and fill the treasury by confiscations. As part of this plan, in 1492 they expropriated and banished the Jews.

The discovery of America was financed by the spoils of the Inquisition. Complete freedom of thought and expression gives joy, but does not appear to be absolutely necessary for the progress of science. The authoritarianism of Babylonia and the Middle Ages did not paralyze science. One may conclude that the authoritarianism rising in contemporary Europe also will not paralyze science, though it may interfere with the personal happiness and comfort of scientists.

In an ideal society, freedom and order should be in perfect equilibrium. If either is in excess, the progress of science is hindered, but it is not stopped. Complete freedom of thought is not the chief condition for the progress of science. There are other social conditions which may assist science more.

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CLOCKS AND MILLS

The oldest mechanical clock whose mechanism is definitely known was built in 1348. Clocks surviving from that date show refinements in the design of their escapements, balances and striking mechanisms which must have been the product of considerable evolution. Villard de Honecourt's sketch of a crude escapement mechanism in 1248 has already been described. It seems that the fundamental principles of the mechanical clock were solved between 1275 and 1350. Some particulars of clocks made between 1232 and 1340 are known, while the construction of some of the twenty clocks built between 1344 and 1370 is known in detail.

These clocks were built in many countries, including Italy, England, France, Germany and Switzerland. Their works were made by smiths who had acquired their skill in the construction of mill gears and mechanisms.

In 1364, Charles V engaged a German clockmaker named de Vick to construct an elaborate clock in the royal palace in Paris. It was completed in 1370, and its design has been recorded in detailed drawings.

The weight which drove the clock weighed a quarter of a ton, and that which drove the striking mechanism weighed three-quarters of a ton. The great weights were needed because the parts were so rough, having been made by a blacksmith on an anvil. The main wheels were about three feet in diameter.

This clock had an important influence in history. When it was finished, Charles V ordered the hours and the quarters to be struck in all the churches of Paris, according to the time

given by the palace clock. This helped to establish the measurement of time by equal hours.

In antiquity time was measured by the length of daylight, which was divided into twelve hours whose length depended on the season of the year. At an early date, astronomers began to use equal hours, and the early Christians also made use of them. In the early medieval period the variable hour was generally used, because the church liturgy was based on the variable hour.

As urban life developed, the civil population made increasing use of the equal hour. When men were bound to the soil and paid in kind, time and efficiency were unimportant, but when craftsmen became independent and could be hired for short periods, the equal hour was the convenient unit for measuring labour and wages. It assisted the organization of production. Charles V's order was an expression of the increasing influence of the new mode of urban production on the organization of social life.

Clocks indicating minutes and seconds were made in the fifteenth century, and one was used in astronomical observations for measuring the interval between the transits of the sun from noon to noon.

Tycho Brahe used mechanical clocks at the end of the sixteenth century. He noted their variation with atmospheric temperature and pressure, and kept them in a room heated to a constant temperature. He found they were not as accurate as a fluid clock in which mercury was used instead of water.

The mechanical skill needed to construct these clocks was developed through the construction of mills. The first power mills for purposes other than grinding grain were used in the textile industry for pounding or fulling cloth.

The records of these occur in the second half of the twelfth century. These machines were trip-hammers, in which a hammer is raised by a cam on a rotating axle. Machines of the same type were used for crushing oak bark, wood and ore. The old-

est drawing of a trip-hammer mill was made by a Hussite engineer in the first half of the fifteenth century. This machine was used for crushing ore. Power-driven grindstones for sharpening metal tools were used in the fourteenth century.

Power was utilized in a variety of machines in the fifteenth century, and the problems of its transmission were gradually formulated to craftsmen.

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47

THE ORIGIN OF MODERN SCIENCE

Social life within the medieval castle or bourg was under the complete personal control of the lord. The various servants and craftsmen who supplied food and armour were organized in a hierarchy of authority under his supervision. Every man had his quarters within the bourg and performed his work under his lord's eye. The feudal knight was accustomed to interpret all relationships in personal terms, and the inhabitants of the bourg commanded by him viewed relationships in the same way. They were in immediate contact with the person of supreme authority. They made articles for those above them, and for themselves. Action to make and do things was due to orders from above. When the needs of superiors were satisfied production stopped, apart from the satisfaction of small personal needs. In such a society, as Veblen has pointed out, the notion of cause and effect is conceived in personal terms, and is subjective. Things happen because some superior has willed them, or because objects are possessed by spirits and demons. The religious view of life, in which God has supreme power and all that happens is due to His Will as performed by His regents, ministers and servants, has the same structure. In fact, medieval theology may be interpreted as the product and parallel in ideas of the social relations between the members of feudal society.

The most important topic of discussion is authority, in the guise of God and the lord, and what is due to it. The members of feudal society are in the habit of looking upwards to the lord, and to heaven. They do not regard their daily activities as of first importance, and worth serious discussion.

The persons who began to aggregate around the walls of the feudal bourgs in the tenth century were not members of the society inside. They had no quarters within the bourg, and no fixed place in its social hierarchy. They did not work directly under the eye and personal supervision of the lord within. The principle of personal authority counted much less with them than with the internal inhabitants. The composition of their society was quite different. They consisted mainly of merchants and vagabond peasants who had become independent craftsmen.

Owing to the stimulation of commerce by the merchants, their numbers rapidly increased, so that presently the population of the faubourg, or surroundings of the bourg, was much larger than the strictly feudal population inside.

The total number and also the percentage of craftsmen in its population was much higher.

In many instances the original bourg was smothered by the new population, and the lord transferred his establishment to a neighboring bourg off the new trade routes and as yet free from the embarrassing new population. He could resume without interference the control of life within his establishment, over the countryside.

The population of the faubourg around his former headquarters now occupied the deserted fortress and converted the whole city into a stronghold of the new bourgeoisie of merchants, adventurers, and independent craftsmen.

This bourgeois society carried over many conceptions from the feudal society in which it had been born, and at first aspired to conduct its life according to the same principles. It became as pious as the nobility and vied with it in gifts to the Church. But its fundamental interests were different and presently came in conflict with those of religious feudal society. Henry Adams has commented on the decline of religious ardour visible in the French ecclesiastical architecture of the fourteenth century. He attributes this to the disappointment of the bour-

geois at the return on their enormous investments in the Church in the previous century. They had found that expensive housing of relics did not bring them much benefit in this life and they began to suspect that it might not in the next.

They had built the cathedrals as a short route to heaven, as their descendants constructed the railways in the nineteenth century to quicken the journey to Paris. The expenditure on religion in the thirteenth century turned out to be a sort of South Sea Scheme, and Adams suggests that the Reformation might be interpreted as a reaction of medieval business men against investment in shrines and relics.

Unlike the feudal nobility, the bourgeoisie did not receive its living in exchange for the conduct of government, but made it by trade and handicraft. The processes of trade and handicraft were more vital to it than problems of authority and precedence, and presently began to compete with them for its attention. As Veblen writes, matter-of-fact knowledge and work-day information were not fit topics of dignified enquiry in feudal society, but the new bourgeoisie began to establish the repute of these topics, along with its own social status.

Successful commerce demands a knowledge of materials. The merchant buying and selling textiles must be able to judge their quality before he can make a good bargain. He studies their feel and appearance, and learns from experience tricks by which they may be tested.

The craftsman handling metals must study their properties in order to make good products. He will note their hardness, elasticity, and rough measures of the temperatures at which they soften and melt. The medieval merchants and craftsmen, like those of antiquity, had a deep interest in, and knowledge of, the properties of materials. But the influence of the bourgeoisie's technical knowledge on medieval society was profoundly different from that of ancient craftsmen on slave civilizations. The bourgeoisie became the ruling class within its own cities, and its technical interests, as those of the ruling

class, naturally tended to become dominant. The merchants and craftsmen of antiquity never became the ruling class, so their processes never became the chief object of study in their time.

The medieval bourgeoisie thus accomplished something that had never been done before. It made the properties of materials the chief interest of the ruling class. This subject, owing to its new repute, was studied for its own sake by rich bourgeois who had some leisure. A systematic knowledge of the properties of matter, or physics, naturally grew out of it. By the sixteenth and seventeenth centuries, when the interests and ideas of the bourgeoisie had begun to dominate the whole of society, great noblemen such as Robert Boyle, unconscious of their acquisition of a bourgeois outlook, were investigating the properties of matter with brilliant success.

The explanation of how an extremely pious nobleman such as Boyle could, in the seventeenth century, earnestly investigate queries, mechanical tools and processes, which to a nobleman of the twelfth century would have seemed blasphemous and socially degrading, also explains the rise of modern science.

This is the most potent contribution to human development since the invention of agriculture. It may ultimately surpass in effect the invention of tools, which converted animals into men, as biological science may show how new and better species of men may be produced.

The bourgeoisie created the conditions in which modern science, which consists of a balanced combination of experiment and theory, could come into existence. But it did not set out to create modern science. In fact, it has treated science meanly, and the majority of its descendants, the modern business men, still require persuasion to spend money on scientific research. The bourgeoisie has pushed through the greatest contribution to culture since neolithic times, largely in spite of itself.

The study of technical processes reveals sequences of rela-

tions between material events. Forces may be applied through the medium of chisels and other instruments, salts may be dissolved by water, and metals melted by fire. These relations are described by the conception of cause and effect between material bodies, and are summarized as laws of nature. This material chain of causation and the laws of nature appear as independent of the personal authority of God and man.

The investigation of the properties of matter seemed to put God outside nature. The servant of the feudal lord tended to put the world within and under God, as he was himself within and under his lord's authority. The feudal conception was vertical in terms of authority, while the bourgeois was horizontal in terms of sequences of cause and effect, in the multiplication of uniform material products spreading over the surface of the earth. Owing to the conflicting directions of their gaze, the feudality and the bourgeoisie were incapable of conceiving the world within the same scheme. The early intellectual bourgeois did not know this. They assumed that the theory of the world engendered by the preconceptions of their class could be harmonized with the feudal theology. In their attempts to achieve this harmony, they created scholasticism, which demonstrated after four centuries of intense disputation that it was impossible.

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THE DEVELOPMENT OF MONEY

Charlemagne's establishment of a unified system of currency, weights and measures in the eighth century had already decayed in the ninth century, because feudal society based on agriculture, and virtually without trade, did not need the standardized units which facilitate exchange.

The population in each district was attached to the soil, and was paid in kind. Such small trading transactions as it made were more conveniently conducted in local units. Agriculture and industry in the early feudal period were conducted without capital.

The rise of trade in the tenth century revived the use of money. As trade increased, towns were founded, and hoards of money were accumulated by the new class of merchants. The rate of increase was on the whole slow. Cunningham states that the volume of trade in Europe did not greatly increase between 1300 and 1600, though the methods of conducting it greatly changed.

Feudal society regarded production as a fixed quantity, based on the unchanging output of agriculture. It did not envisage a cumulative increase of production and improvement of technique, though this occurred. As it had no use for capital, it denied the legitimacy of usury, and enforced its opinion through the Church by the precept "Take ye not interest from loans."

The new class of merchants who owned the growing hoards of money struggled to obey, but with indifferent success. During the twelfth and thirteenth centuries they often directed in

their wills that gains from usury should be repaid. This custom disappeared by the end of the Middle Ages.

The merchants devised subtle evasions of the ecclesiastical law. They asserted that the practice of usury with borrowed money was not a sin, and they used fine phrases, such as reward, gratuity and consideration, to disguise it. But the feudalists, and their scholastic exponents, remained suspicious, and as Pirenne says, they "could hardly imagine the merchant's strong-box without picturing the devil squatting on the lid."

In the twelfth and thirteenth centuries money was lent almost entirely on the security of crown jewels and land, for financing wars and courts. It was not lent for enterprise, but for unproductive consumption, and ultimately medieval bankers were ruined by this system.

As the Church's ban on usury made money-lending difficult for Christian merchants, non-Christians tended to meet the demand.

Ehrenberg mentions that the first general persecution of the Jews occurred in 1096, and the first known record of their money-lending occurs in the same year. They were gradually displaced from money-lending by the north Italians, and then by the Florentines. They were displaced from the larger money business in England, France and the Netherlands before the end of the thirteenth century. The first professional Christian money-lenders were the collectors of papal dues.

As early medieval production did not need capital, and usury was risky, there were few opportunities for the profitable employment of money. Import and export trade provided the best, and accordingly the development of financial technique started in the ports. As the first of these in Europe were Italian, the principles of modern finance were invented by Italians.

Banking, which grew out of money-changing, bills of exchange, the lending of money at interest and commercial companies were introduced to Europe or invented by Italians. As

cargoes are large and expensive, their purchase often requires the cooperation of several lenders. When this technique had become familiar, it could be used for other purposes, such as the financing of public buildings. The first known voluntary loan to the Venetian Republic was made by seven persons in 1164.

The possibility of making large profits on the investment of money in trade gave a new type of stimulus to production. The merchants in ports wanted more things to trade with. They urged the production of a surplus of goods above the needs of the local population. This was contrary to the general medieval conception, which regarded the town and its surrounding country as a self-supporting unit. Venice specialized in the manufacture of glass and silk, Genoa in arms, and Florence in the working and dressing of cloth.

As Florence was an inland town, her merchants could not invest their profits in the general trade of a port, so they presently specialized in money-lending.

In the Middle Ages, the craftsmen owned the raw material which they turned into goods. The engagement of craftsmen to work on raw materials owned by capitalists and sold by them after finishing occurred at Florence at the beginning of the fourteenth century. The Florentines specialized in dyeing and finishing raw cloth imported from Flanders. The trans-European trade in this cloth required considerable quantities of capital, and the merchants who profited by it could lend their gains for usury, which often produced larger and quicker profits. A monetary and credit system gradually evolved out of the early Middle Ages' system of dealing in kind.

Accumulation of money, and skill in handling it, made Florence the first banking centre in Europe. Feudal kings who could not find money within their own society found that they could borrow from the Florentine bankers. This gave a powerful stimulation both to warfare and to banking. Feudal military chiefs had hitherto projected campaigns on the basis

of their immediate resources of soldiers and equipment. They now found that they could project much greater campaigns with the increased number of soldiers and arms available through borrowed money.

One effect of this was to increase the size of social organization. Successful feudal chiefs became monarchs of unified nations. This occurred first in England and France. The English were particularly fortunate because the whole country had been conquered by William, who was a feudal duke and not a king. The country belonged to him and to his descendants as a feudal estate. The head of the country was determined by inheritance and not by election. The emperors of Germany and the kings of France were elected from co-equal feudal lords, and the bonds of allegiance were weak. In Italy, the kingship belonged to the Holy Roman Emperor, but it was a nominal title.

The stability of the English hereditary monarchy had great importance. The English barons and bourgeoisie recognized the legitimacy of their title, even through disaster. Instead of dismissing a disastrous king, they inclined to make him submit to some degree of control. The early English kings tried to achieve their ambitions without consulting the barons and bourgeoisie, by borrowing money from Florence. This method was curtailed in 1339, when Edward III went bankrupt and in turn bankrupted the Florentines from whom he had borrowed.

Edward III was forced to borrow from his own citizens, and surrender financial independence. But this had the effect of turning the king's wars into national wars, and increasing the size of military operations. England and France settled on a hundred years of international war.

The financial resources of England and France were insufficient to meet their kings' needs, and the Florentine bankers recovered. The leaders of the second period of Florentine banking were the Medici. Their family became established in

Florence in the thirteenth century, but they lent money for three generations before they became the chief bankers in the city. They became leading international money-lenders only in the fifth generation. Giovanni de' Medici made a fortune by ransoming a pope, and the family remained bankers to the papacy until 1476. The family spent 36,000 florins on taxes, public buildings and charity between 1391 and 1434.

Ardigo de' Medici became leader of the guilds, and the popular party triumphed under him about 1314, and Dante, who belonged to the aristocratic party, was exiled. Silvestro de' Medici became leader of the wool carders in the fourteenth century. Cosimo the Elder ruled Florence for thirty years merely by financial power. He was very keen, intelligent and implacable. As a bourgeois, he did not care for titles, and he strengthened both his financial and political power by leading the lower classes against the nobles. He ruined the nobles by financial operations, and when they resisted by force, he incited the populace against them. All financial rivals were destroyed and he was enthusiastically supported by the people. He claimed that his acts were always "for the good of the lower classes, for the good of the people."

He paralyzed hostile foreign powers by threatening to close his credit business, defeating in this way an alliance of Venice and Naples against him.

He and his descendants had their enemies hung by the heels, and engaged artists such as Leonardo da Vinci to make sketches of them in this position.

Cosimo the Elder once said that he would like to have "God the Father, God the Son, and God the Holy Ghost all on my books as debtors."

He and his grandson Lorenzo were interested in Platonism, and engaged Brunelleschi, Ghiberti, Luca della Robbia, Ghirlandaio, Botticelli, Michelangelo and others to build and decorate their palaces in Florence. Between 1434 and 1471 the family spent 663,000 florins on public services in the city. Lorenzo

the Magnificent, who lived from 1449 to 1492, did not distinguish between his own and the city's finances.

The Medici and other banks owed their acquisition of political power entirely to wealth and skill in finance. Banking was revealed as a new method of obtaining power.

Financiers gained political importance in the fourteenth century, and the bourgeoisie in the fifteenth century, when it became the third estate. The condition of the fourth estate, or the majority of the people, became, after the fourteenth century, far less tolerable than in the previous two hundred years, owing to the decay of its medieval rights. Pirenne remarks that the nobles of the fourteenth and the beginning of the fifteenth century, though numerous, were remarkably sterile in achievement, and showed marks of class degeneration.

The Florentines abolished serfdom by decree in 1415. This was followed by technical improvements in agriculture. Rice cultivation was introduced into Lombardy in the fifteenth century, the cultivation of the silk worm was started in the Midi, in Flanders the triennial rotation of crops was abandoned, and fallow was sown with clover. Spain and England sacrificed the cultivation of cereals to sheep-farming.

A proletariat appeared about 1450 which had lost the protection lent by organization in guilds, and was completely at the mercy of the employer.

The development of commerce reestablished the ancient saying that "money is the sinews of war."

The procuration of money for financing war became the chief economic topic in the Renaissance. When Louis XII of France decided in 1499 to conquer Milan, the condottiere captain whom he consulted on means replied, "Most Gracious King, three things must be ready: money, money and once again money!"

Machiavelli believed that if one had soldiers one could find money. He was opposed in this opinion by his friend the great historian Guicciardini, who was not so farsighted in theory, but

had a better judgment of contemporary politics. Their disputes foreshadowed the main problems of modern social science, concerning the conflict between labour and capital.

The Italian cities were the first powers which accumulated sufficient money to be able to prosecute war by its means. They could afford to pay soldiers, whereas feudal princes could not.

The feudal military system had been an advance on that of the German tribes, in which there was no division of labour and all free men were liable to bear arms. The feudal vassal could not be asked to perform more than his feudal due, and was therefore not under strict military control. The cities, with their still greater division of labour, were able to create a class of paid soldiers under permanent discipline.

Under the feudal system arms had been a profession. Through these mercenaries, who arose in the fourteenth and fifteenth centuries, it developed into a form of manual labour.

The invention of cannon in the fourteenth century, and of muskets in Germany about 1459, made military equipment far more expensive, and converted the supply of arms into a heavy industry requiring large capital.

Spears, swords, bows and arrows could be made by soldiers and blacksmiths, but iron-founding was a highly-skilled specialist's industry.

The supply of armaments was the department of production in which the transformation of dealing in kind into a money and credit system proceeded most swiftly.

In Italy the conduct of war became the province of private companies of condottieri, or mercenaries. Whereas the feudal duty to serve was based on a public code, the engagement of mercenaries obeyed the laws of private property, and in effect made blood purchasable by money.

Warfare became a more democratic pursuit, in which the skill of engineers, gun-founders and artillerists was of the first importance, and the men who had this knowledge belonged to

a class other than the nobility. The nobility in the Italian cities abandoned the profession of arms in the fourteenth century and the population did not undertake their own military defence.

The discovery that money could give more power than feudal rights undermined feudalism. The population of the Italian cities treated feudal lords and serfs with scorn when they found they had the power, and the release from feudal subjection gave them a great new confidence. They had found that money and commercial enterprise were stronger than the feudal system, so they cultivated wealth and individualism. This was contrary to the doctrine of the Church and the scholastic philosophers.

As Ehrenberg explains, they searched eagerly for an alternative to the medieval authorities and found it in the classics. They did not turn to the classics because they were fond of philosophy and archaeology, but because they needed a rival to the wisdom, sanctified by age and faith, of the schoolmen.

The Renaissance, or re-birth of classical learning, was in effect a manœuvre by the triumphant bankers and merchants to fortify their new ruling position with cultural defences. As Pirenne remarks, the urban spirit must be regarded as the prime and remote cause of the Renaissance. If that movement had been due merely to the recovery of classical literature, it would have occurred in Charlemagne's time.

The success of the new moneyed classes and their methods of making a living gave prestige to social novelty and experience. When feudal men saw that money-lenders, the class held in deepest contempt by feudal society, could become lords of the world, their principles were shaken, and they felt impelled to give more attention to the facts of experience and the possibility of novelty.

The confidence that entirely new things were possible encouraged the search for them. Man studied nature and human

nature, and became interested in himself. So while one set of intellectual leaders disinterred the classics, another set explored the possibilities of men and things. Both sets presently became fascinated by the discoveries revealed through the new direction of their interest. The influence of the first set was in many ways reactionary. Dante showed the new comprehension of the variety of personality, and confessed his desire for fame, which was a classical and not a medieval conception; he was perhaps the first modern man who ascended a mountain to admire the view. Petrarch also admired mountain scenery, which was regarded with horror by medieval men. They revived the social ideas of the old slave civilization. They disdained manual labour, and created the prejudice in favour of the liberal professions, which still survives. Pirenne considers that this prejudice is "largely responsible for the indifference to the lot of the lower classes which characterizes the modern era."

Cosimo de' Medici encouraged Platonic philosophy as "the fairest flower of the ancient world of thought"; Lorenzo the Magnificent patronized scholars such as Argyropoulos, Ficino, Valori, Acciajuoli, Pandolfini and Pico della Mirandola. But he did not support the second set, which included Leonardo da Vinci, Pacioli, Toscanelli, Amerigo Vespucci, and other Florentines who were advancing towards the discovery of America and modern science, and he destroyed the independence of Florence. The first set, known as Humanists, encouraged the search for antique statues and the architectural study of the ruins of ancient buildings. They discovered a manuscript of Vitruvius, which much influenced the practice of architecture. The renewed study of the science in this, and other manuscripts, such as those of Archimedes, did not have very important results. Much of their contents had been superseded by new scientific knowledge slowly accumulated during the Middle Ages. In some cases, they depressed science by dis-

crediting new knowledge, as, for instance, the work of Jordanus III on the lever, in favour of Archimedes' less fertile methods.

The study of ancient sculpture and architecture provided an art that could be set against the Gothic, which was a symbol of feudal culture. The self-indulgence of the new rulers emancipated from medieval doctrine was justified by citation of the habits of Roman emperors, and political assassins and conspirators appealed to the memory of Brutus and Catiline.

The new social system based on commerce and credit could not be operated by men without intellectual ability.

The Italian bankers who became rulers were abler than their feudal contemporaries, and knew how to base policy on economic statistics. As they were a new ruling class, they were free from the caste-feeling of feudalism, and their business made them use men of every social class. This fostered the esteem of ability, and led on to the cult of personality and the admiration of any sort of behaviour, as long as it was interesting.

Numerous independent cities and individualists of many sorts grew in the new soil of a commercial society. They became superior in credit and industrial technique, and in personality to the men of the North, where feudalism lingered. But while Italian society was becoming more varied, it was also disintegrating. Less advanced countries, such as England and France, were developing national unity, though dependent for cultural progress on the Italians. For five hundred years after the Norman Conquest, there was virtually no important contribution to culture that was specifically English. But when the centre of the world was transferred from the Mediterranean to the Atlantic by the discovery of America, England was able to take advantage of the new opportunity created for her by circumstances, because her population was unified in a relatively stable social system.

The Italian statesmen were acutely conscious of the anarchic weakness of their country, but their policy was governed, in spite of their judgment, by the tradition of individualism created by the new commercial societies. The most determined attempt to unify Italy was made by Caesar Borgia.

He was a Spaniard and did not possess the individualist feeling of the commercial Italian. It is thought that he aimed at the destruction of the Papacy, which attracted so much foreign intervention in Italy. This policy secured Machiavelli's secret admiration and he believed that the existence of the Papacy was the cause of Italian disunity. The city republics and principalities could not be forced to cooperate while foreign powers were setting them against each other, in plots aiming at the control of the Church's political policy.

Caesar Borgia annihilated the Orsini and Colonna factions, which had prevented any social stability in Rome. He forced his father, Alexander, who was the Pope, to assist in systematic murders of the higher officials of the Church, to secure their influence and incomes. The Venetian ambassador reported in 1500 that "every night four or five murdered men are discovered—bishops, prelates and others."

When Caesar had destroyed a large part of the higher officials of the Church, and had terrorized his father into acquiescence in the murder of his best-loved son, and was ready to destroy his father, too, and seize the Papacy, he accidentally poisoned himself and his father with a sweetmeat intended for another.

This accident defeated his plan. The horrors of his reign had stirred the conscience of the Papacy, and when he was gone, this led to internal reforms. His attempt to destroy the Papacy promoted its revival and his failure left Italy disunited. Pirenne remarks that "the absence of any political unity in Italy, which Machiavelli regretted so bitterly, was doubtless the condition of her breaking with the past. Never having been squeezed

into a single state, Italy was then able to become, in respect of the rest of Europe, something of what ancient Greece was for Rome."

Caesar Borgia had demonstrated that unity cannot be imposed if the social system operates according to individualistic principles and has trained its members in individualistic forms of behaviour. Under these circumstances the extremest use of force fails, even when applied by the ablest men, for he had recruited the best soldiers and officers in Italy, and had engaged Leonardo da Vinci as his chief engineer.

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BORGIA'S ENGINEER

Leonardo da Vinci was born near Florence in 1452. He was the illegitimate son of an able lawyer who became one of the chief legal advisers to the Medici. He showed remarkable artistic talent in his youth, and was apprenticed in the shop of Andrea Verrocchio, a distinguished painter, goldsmith and craftsman who, like many of his colleagues, had some knowledge of sculpture, architecture and engineering.

Verrocchio had adopted the naturalistic style of painting developed by Masaccio, which emphasized fidelity to observation and analysis of the structure of a subject. This required a thorough knowledge of the optics of perspective and human anatomy.

An apprentice in Verrocchio's shop would also learn the techniques of gold-working and sculpture. These involved metallurgical knowledge concerning the casting of gold and bronze, and the preparation of alloys. As the craftsmen had to prepare their own paints and materials, and could not buy them ready-made, they needed a considerable knowledge of chemistry.

F. I. G. Rawlins has remarked that "the studio of the medieval artist or craftsman was very much more than a place where pictures were painted or pots were fashioned. It combined the functions of workshop and laboratory for the master's own activities, and for the instruction of his pupils. A long apprenticeship was demanded of those whose ambition it was to become master-craftsmen, and much of this period seems to have been devoted to an intense and intimate study of materials,

which included the preparation of pigments and the application of sundry metallurgical principles, such as those of metal refining and extraction. In a word, this was a hard school of training in the properties of matter."

Artists were also expected to organize the festivals that were an important feature of contemporary social life. They had to paint masks and construct entertaining mechanical puppets. As architects, they had to learn the elements of statics and the mechanics of lifting machinery.

A person with an aptitude for one or more of these techniques could learn in an eminent shop such as Verrocchio's much of what was known about them.

Leonardo quickly mastered the existing knowledge in all of these techniques. He was interested in everything and fond of discussions with other experts. After he had completed his apprenticeship and joined the guild of painters, he became a notable figure, very strong and beautiful as he "stood in rose-coloured cloak and rich gold hair," talking to his friends.

He received a few commissions from the Medici, but they were interested in the application of painting to literary interests rather than in the significance of painting and the information its processes reveal about the nature of the world and man.

Leonardo apparently did not feel that his interests in the crafts and mechanics were congenial to the Medici, and looked elsewhere for an opportunity. He became painter and engineer to Ludovico Sforza in Milan, and remained there until 1499, when the city was captured by the French. He returned to Florence, but was unable to secure a satisfactory appointment. He was engaged by Borgia as chief engineer in 1502, and travelled through Italy advising on military constructions during 1503.

When Borgia's policy failed, he had to seek another position and returned to Milan under French patronage. He lived in Rome from 1513 to 1517, and advised the Papal Mint on tech-

nical processes, and amused the ecclestiastical authorities with mechanical toys. His experiences were unsatisfactory, so he accepted a position as painter and engineer at the French court. He settled in the south of France and died there three years later, in 1519.

Leonardo first left Florence about 1483. Calvin has suggested that "his exclusive belief in experimental methods and slight regard for mere authority whether in science or art made the intellectual atmosphere of the Medicean circle, with its passionate mixed cult of the classic past and of a Christianity mystically blended and reconciled with Platonism, uncongenial to him."

He applied to Ludovico Sforza, who had usurped the control of the principality of Milan, for an appointment. Ludovico was engaging writers, artists and engineers to celebrate, embellish and strengthen his state and so justify his usurpation.

A draft of Leonardo's letter of application exists and reads:

"Most illustrious Lord. Having now sufficiently considered the specimens of all those who proclaim themselves skilled contrivers of instruments of war, and that the invention and operation of the said instruments are nothing different to those in common use, I shall endeavor, without prejudice to anyone else, to explain myself to your Excellency, showing your Lordship my secrets, and then offering them to your best pleasure and approbation to work with effect at opportune moments as well as all those things which, in part, shall be briefly noted below.

"1. I have a sort of extremely light and strong bridges, adapted to be most easily carried, and with them you may pursue, and at any time flee from the enemy; and others, secure and indestructible by fire and battle, easy and convenient to lift and place. Also methods of burning and destroying those of the enemy.

"2. I know how, when a place is besieged, to take the water

out of the trenches, and make endless variety of bridges, and covered ways and ladders, and other machines pertaining to such expeditions.

"3. Item: If, by reason of the height of the banks, or the strength of the place and its position, it is impossible, when besieging a place, to avail oneself of the plan of bombardment, I have methods for destroying every rock or other fortress, even if it were founded on a rock.

"4. Again I have kinds of mortars; most convenient and easy to carry; and with these can fling small stones almost resembling a storm; and with the smoke of these causing great terror to the enemy, to his great detriment and confusion.

"9. And when the fight should be at sea I have kinds of many machines most efficient for offence and defence; and vessels which will resist the attack of the largest guns and powder and fumes.

"5. Item: I have means by secret and tortuous mines and ways, made without noise to reach a designated spot even if it were needed to pass under a trench or a river.

"6. Item: I will make covered chariots, safe and unattackable, which, entering among the enemy with their artillery, there is no body of men so great but they would break them. And behind these, infantry could follow quite unhurt and without any hindrance.

"7. Item: In case of need I will make big guns, mortars and light ordnance of fine and useful forms, out of the common type.

"8. Where the operation of bombardment should fail, I would contrive catapults, mangonels, *trabocchi* and other machines of marvellous efficacy and not in common use. And in short, according to the variety of cases, I can contrive various and endless means of offence and defence.

"10. In time of peace I believe I can give perfect satisfaction and to the equal of any other in architecture and the com-

position of buildings public and private; and in guiding water from one place to another.

"Item: I can carry out sculpture in marble, bronze or clay, and also in painting whatever may be done, and as well as any other, be he whom he may.

"(32) Again, the bronze horse may be taken in hand, which is to be the immortal glory and eternal honour of the prince your father of happy memory, and of the illustrious house of Sforza.

"And if any of the above-named things seem to anyone to be impossible or not feasible, I am most ready to make the experiment in your park, or in whatever place may please Your Excellency—to whom I commend myself with the utmost humility, etc."

Leonardo gave the first place in this application to military engineering, and the second to civil engineering. He mentions his qualification as a painter incidentally. The draft exhibits worldly sense, and was skilfully composed to appeal to Ludovico. It has often been said that it did not express his own opinion of the relative worth of his work in painting and in other subjects, but it does agree with the distribution of energy in the works that survived. He was the first painter who utilized the contrast of light and shade. His predecessors had been restricted to line and colour. He was the first to eliminate stiffness in the depiction of human figures and make them appear fully alive. The contributions form a considerable fraction of the whole technique of painting. But he finished very few pictures. Not more than twelve have survived.

In contrast, he left five thousand pages of manuscript notes on scientific and technical researches. These included several treatises in which a general problem, such as flight, was investigated systematically, and hundreds of notes on isolated problems.

When Leonardo studied, sciences were not well defined.

His researches would now be classified under engineering, mechanics, hydraulics, aerodynamics, and anatomy, with striking comments and isolated experiments in physics, geology, physiology, botany and meteorology.

He began to make these notes before he left Florence in 1483, and added to them until he died in 1519. They are the product of forty years of continuous effort, and form one of the largest and most sustained intellectual efforts that has been made by man. One wonders, then, how Leonardo has acquired the reputation of a finicking genius who made a disappointingly small use of his great gifts. This has arisen through the contrast in intelligibility between his work in painting and in science.

His paintings present their meaning directly. As he defined a good painting by the degree of perfection with which it imitated nature, he meant his paintings to have the maximum degree of intelligibility. Everyone, according to the measure of his intelligence, could directly apprehend their merit.

But access to the meaning of his scientific researches was not so direct. Though they are illustrated by thousands of his sketches, they are written in mirror-writing. He was left-handed and could write more easily backwards, from right to left. This prevented his manuscripts from being read without special training. In addition, his notes were discursive, and had not been prepared for publication. Thoughts on quite different aspects of nature were often jotted down on the same page at different times, presenting the reader with a fascinating but perplexing jumble.

He apologized for this in a note written in 1508. He says: "This will be a collection without order, made up of many sheets which I have copied here, hoping afterwards to arrange them in order in their proper places according to subjects of which they treat; and I believe before I am at the end of this, I shall have to repeat the same thing several times; and therefore, O reader, blame me not, because the subjects are many.

and the memory cannot retain them and say, 'This I will not write because I have already written it.' "

This passage shows that Leonardo intended his notes to be read, and did not wish to make them difficult and mysterious. His verbal explanations were often obscure, because the terminology of science was still crude, and his results frequently contained new knowledge for which there was necessarily no name.

These are the primary reasons why Leonardo's achievements have been so much misunderstood. The main volume of his work was done in science, and owing to the form of expression and the newness of the ideas it was as unintelligible to his contemporaries as a treatise in German on the theory of relativity is unintelligible today to an Englishman who knows no mathematics or German.

The difficulty of completing a scientific investigation was far greater then than now, as the evolution of the scientific method was not yet complete. The miscellaneousness of Leonardo's researches corresponds to the stage reached in the evolution of scientific method in his day. But the old complaint that he failed to complete his works through finicking is not entirely unjust. He worked excessively slowly at his paintings, and he doubtless might have put his scientific notes into publishable form. He could have employed a secretary to transcribe them into normal handwriting.

The descriptions, sketches and proposals of military inventions in his notebooks include tanks, breech-loading cannon, rifled firearms, wheel-locked pistols, steam cannon, and submarines. Of the latter he writes that he must explain "how and why I do not describe my method of remaining under the water for as long a time as I can remain without food; and this I do not publish or divulge on account of the evil nature of men who would practice assassinations at the bottom of the seas by breaking the ships in their lowest parts and sinking them together with the crews who are in them."

He invented the life-belt and diving suit. He gives numerous sketches of attachments for divers' face-masks, nose-clips, and tubes for supplying fresh air to the diver. He depicts a lively figure of a youth skiing over the water on bladders attached to his feet, pushing and supporting himself by sticks with floats on their ends. He sketches various designs of paddle boats driven by hand- or foot-cranks.

He invented the polygonal fortress with outworks, later ascribed to Dürer and Lorini.

His work on canalization had military and civil applications. He proposed a canal two hundred miles long through Lombardy, which would pass over mountains, and he was consulted by the officers of the Florentine army besieging Pisa on the project of diverting the river Arno, so that the city would be starved of supplies. He made improvements in canal locks and gates, and invented dredges of two types later ascribed to Besson.

His contributions to architecture included designs for elevated streets. The visitors, and wood and wine and such things, were to enter the houses by the elevated streets, while sewage and other evil-smelling things were to be removed by the lower street. He designed horse-stalls which could be kept clean, and a chimney which rotated with the wind, to prevent smoke from being blown back into rooms.

He gave detailed attention to the design of textile machinery. The textile trade and industry had been the foundation of Florence's power, and the improvements he proposed would have increased its ability to meet competition. His proposals and sketches include a rope-making machine which foreshadowed that of March; silk doubling and winding machines of types ascribed later to Zonca; and woollen spinning machines of a design later ascribed to Jurgens.

He gave an incomplete sketch of a power loom, and sketches of a gig mill for raising the nap on felt and a shearing engine for cutting cloth and felt hats.

Usher remarks that apart from silk reeling and twisting and the fulling mill, increasing the homogeneity of cloth by clamping, all textile inventions used in western Europe had been acquired from the Near East. Leonardo's notebooks reveal an attempt to apply power to the chief textile machines. The power was to be obtained from water mills or horse-driven winches. Water power had probably been applied to silk reeling and twisting prior to Leonardo.

He was aware of the significance of his design for the power loom. He wrote under it: "This is second only to the printing press in importance; no less useful in its practical application; a lucrative, beautiful and subtle invention."

His spinning machine had a flyer which guided the thread, evenly wound the bobbin, and would mount four spindles simultaneously.

He was consulted by the Papal Mint on the improvement of coining during his residence in Rome from 1513 to 1516.

He sketched elaborate designs for rolling, drawing and hammering gold bars. Rolling and drawing had been used for light work at least since the twelfth century, but Leonardo proposed to apply them to heavy work. He also proposed improved methods of stamping out the blanks for coins. Improved coining machinery inspired by Leonardo's designs was subsequently constructed at Augsburg and Nürnberg, the centres of the financial activities of the Fugger.

He sketched designs for scores of new and improved machine tools. He invented the anti-friction roller bearing. He made beautiful sketches of link chains, exactly similar to those now used on bicycles. These were later ascribed to Vaucanson and Galle. He sketched a universal joint before Cardan or Hooke. He sketched bevel, spiral and stepped gears, and varieties of cranks and gears for converting longitudinal into rotary motion. He sketched a machine for cutting files automatically, and a screw-cutting machine, in which the pitch of the cut screw could be varied by gears from standard leading screws.

He sketched paraboloid compasses, later ascribed to Galileo, and proportional compasses later ascribed to Burgi.

He sketched the turret windmill, later ascribed to the Dutch, and the wheelbarrow, later ascribed to Pascal and Agricola.

He sketched varieties of cranes and presses, including a prevision of the hydraulic press of Bramah.

His treatise on flight contains sketches for the parachute. This invention was later ascribed to Lenormand. He says: "If a man have a tent roof of calked linen 12 bracci broad and 12 bracci high, he will be able to let himself fall from any great height without danger to himself."

He invented the helicopter and made small models that would soar. He made thin wax figures which floated in the atmosphere when filled with hot air.

His sketches show that he must have spent much time in textile and engineering shops. He has left a notable drawing of an arsenal foundry. Leonardo's interest in machines inspired him to search for the laws that governed their operation. He made extensive attempts by observation, logic and experiment to derive the laws of statics and the elementary laws of motion from the study of tensions in pulley strings, inclined planes, collisions, sliding and falling bodies, etc. His notes on these problems, with their neat figures, resemble very much the familiar modern textbook on elementary mechanics, though the incidental comments are much more philosophical and personal. They have been analyzed by Hart. In the course of the discussion of particular problems, he enumerates laws of motion. He says: "Nothing whatever can be moved by itself but its motion is effected through another." Again, "All movement tends to maintenance, or rather all moved bodies continue to move as long as the impression of the force of their motors remains in them." He deduced this from the flight of birds.

While analyzing the operation of the parachute, he remarks that "an object offers as much resistance to the air as the air does

to the object." He investigated the fall of heavy bodies and stated that "a weight which has no support falls by the shortest route to the lowest point, which is the centre of the world." "In the air of uniform density, the heavy body which falls at each stage of time acquires a degree of movement more than the degree of the preceding time."

He dropped weights from a tower, and convinced himself that they did not fall vertically. He believed he could detect a small easterly deviation in the point of impact; and he ascribed this to the earth's rotation. He described the path of the falling body as "a combination of a straight and a curved line. It is a straight line because the body is always found on the shortest line which joins it from [the point of fall] to the centre of the earth. It is a curved line in itself and in every point of the path." This, and other examples, show he had some conception of the parallelogram of velocities. He also had some conception of the parallelogram of forces. He discussed the forces acting on a body lying on an inclined plane. He said "that the weight of the body divides its gravity in two aspects, that is, according to the line [along the inclined plane] and according to the line [perpendicular to the inclined plane]."

He stated that the ratio of the rapidity of movement of a sphere sliding down an inclined plane to that of a body falling freely was as the height of the vertical fall to the length of the inclined plane.

In his analysis of the movements of weights on a system of pulleys he said, "If a force carries a weight in a certain time through a definite distance, the same force will carry half the body in the same time through double the path." This expresses the principle of work.

He had some conception of energy and power, as he noted that "if a wheel is moved for a moment by a quantity of water, and if this water is not added to either by flowing or by quantity, or by a greater fall, the function of this water is finished." He was quite clear on the impossibility of perpetual motion.

He said: "Oh speculators on perpetual motion, how many vain projects of the like character you have created! Go and be the companions of the searchers after gold!"

He made experiments on the recoil of spheres from plane surfaces, perhaps from a desire to understand the effect of the percussion of cannon balls on the walls of fortresses. He concluded that "the blow will be less powerful than its impulse according as the angle of its percussion is nearer the right angle," and he believed that the angles of incidence and rebound were equal.

Leonardo drew many of his theoretical conclusions from the analysis of difficult subjects, such as the movements of birds in flight, and the human figure. He said that "mechanical science is very noble and useful beyond all others, for by its means all animated bodies which have movement perform their operations; which movement proceeds from their centre of gravity."

His advocacy of the study of mechanics as a key to the movements of living organisms is unusual, for according to the naïve view, the movements of living organisms are governed by laws specific to living organisms, and different from those governing the movements of machines and dead matter. Leonardo even advocates the study of human anatomy in order to appreciate movements of the body as illustrations of the laws of mechanics.

He found the centre of gravity of a bird from experiments on a model. He noted that "occasionally the centre of gravity is to be found outside of the body."

He interpreted the manoeuvres of flying birds from the relations between the varying positions of the centres of gravity and pressure. "When a bird which is in equilibrium throws the centre of resistance of the wings behind the centre of gravity, then it will descend with its head downwards." He deduced the functions of the tail and illustrated them by models.

He noticed the elements of streamline when he remarked that "the wings being convex above and concave below, the air escapes more easily the percussion of the wings with elevation than with lowering." He distinguished between apparent and effective wing surface. He advocated high flying to escape turbulence, and give time and space for recovery. He tried to deduce the principles of soaring, and made numerous exquisite sketches of soaring birds in various positions. This part of his programme was first solved by the German gliders after the war of 1914. They were prevented from military flying by the Treaty of Versailles, so they concentrated on engineless gliders, on which there were no restrictions, and discovered how to soar and make long flights in them.

His lengthy studies of water and waves, eddies and pressures were inspired by the desire to understand the motion of the invisible air and its relation to flight. For the attainment of "the true science of the movement of birds in the air it is necessary to give first the science of the winds, which we will establish by means of the movements of water."

His interest in canalization and pumping also stimulated his researches on hydrostatics and hydrodynamics. His investigations of fluid flow, of wave-motion, of pressure in connected tubes, and the influence of pressure on rate of flow contained observations later ascribed to Castelli, Newton, l'Emy, Pascal, Stevinus and Galileo. His proposal to drive a pump by a pendulum was later ascribed to Ramelli and Besson. His proposals for improvement in the details of pumps were later ascribed to Ramelli, and his water screw consisting of coiled pipes to de Rubeis. He also suggested the centrifugal pump.

Leonardo was the first to deduce the centre of gravity of solid figures. He correctly calculated the centre of gravity of the tetrahedron. His result was later ascribed to Commandin and Maurolycus.

He made experimental investigations on friction and concluded that the amount of friction was independent of the

areas in contact. He found that smoothing and lubrication reduced friction, and that if bodies had the same degree of smoothness, the friction was proportional to the pressure between them. He concluded from his experiments on the sliding of a variety of bodies on a horizontal polished surface that the frictional resistance to motion was equal to one quarter of the weight of the sliding body. He recognized the existence of the coefficient of friction, which seemed, according to his experiments, to be the same for all bodies on a polished surface. As Hart observes, this was "the first presentation in scientific history of any laws of friction whatever."

His experiments on the deflection of struts and beams are almost as interesting. They probably arose out of his architectural work. He showed that if one thousand rushes are bound together tightly, they will support more than twelve times the collective weight which could be borne when distributed on them singly. His theoretical analysis of bending under load was roughly correct.

He has left the earliest known example of the use of graphical methods in science. He found the relation between time and velocity in a falling body. Time was plotted vertically, and velocity horizontally.

Leonardo did not understand that force is proportional to acceleration and not to velocity. He said that "if a force moves a body in a given time over a given distance, the same force will move half this mass through the same distance in half the time." He did not recognize the principle of moments. He did not recognize the general principles of the parallelograms of forces and velocities, though he handled many particular cases correctly. His theory of the inclined plane was correct, but not complete, like that of Stevinus. He made some of the classical mistakes of students of mechanics. For instance, he believed that if the rope in a tug-of-war were held in equilibrium by the two contending parties, and each party were hauling with a force of four units, then the tension in the rope

would be equal to eight units. He had forgotten that he had noticed in another problem that action and reaction are equal and opposite.

Though he said that "there is no certainty in sciences to which one of the mathematical sciences cannot be applied, or which are not in relationship with these mathematics," he was a poor calculator, and made many errors in simple arithmetic.

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THE EIGHTH MONTH OF SCIENCE

Leonardo's first profession was painting. This led to studies of anatomy, which assisted him to surpass his predecessors in giving life to his figures. His sense of mechanics, strengthened by his studies of industrial and military machinery, brought the dynamics of living matter to his attention, and predisposed him to combine physiological with anatomical investigations. He injected melted wax into a brain removed from the cranium, to discover the structure of the ventricles. He gave the instruction: "Make two air-holes in the horn of the larger ventricle and inject the melted wax into it, at the same time making a hole in the *memoria* and fill through such a hole the three ventricles of the brain; and then when the wax has hardened, remove the brain and you will see the exact form of the three ventricles. But first insert the fine tubes into the air-holes, so that the air in the ventricles can stream out, giving place to the injected wax."

Four centuries later, anatomists were still claiming priority in the invention of this method.

He discovered from experiments on frogs that the spinal cord was biologically prior to the brain. He said: "The frog retains life for some hours after the head, heart, and intestines are removed . . ." but it "instantly dies when its spinal cord is perforated. . . . It thus seems that here lies the fundamentum of motion and of life."

He noted in his studies of the lung that "dust is injurious," and he seems to have conceived that it was the cause of lung diseases.

One quarter of his anatomical drawings deal with the heart. He made detailed experimental investigations of its structure and function. He showed that Galen's teaching that air is carried direct to the heart by the pulmonary vein, and that the heart has two cavities only, is wrong. He proved that the heart possesses four cavities, and he investigated the movement of blood through them by models. He made a wax cast over the ventricles and their vessels. He made a gypsum mould from the wax cast, and took an impression from it in glass. He examined through this glass model the vortices made by the blood when driven by the contraction into the arteries. He also showed that the valves allow the blood to flow in one direction only. His contract to make a great equestrian statue of Francesco Sforza had particularly stimulated his interest in the anatomy of the horse, and he noted that "in order to compare the skeleton of a horse with that of a man, you must present the man on tiptoe, when portraying the bones." He noted for further consideration "the affinity which the conformity of bones and muscles of animals have with the bones and muscles of man."

Hopstock states that no one before Leonardo, so far as is known, made so many dissections on human bodies, and interpreted them so well. His account of the uterus was far more accurate and intelligible, and he was the first to give a correct general description of the human skeleton, and a correct picture of nearly all of the muscles in the human body. Besides his use of injections and casts, he was the first who employed serial sections. So far as is known, he was the first to have illustrated anatomy by drawings from the object.

Leonardo made sustained studies of meteorological and geological phenomena. He recognized the meaning of the existence of fossils on the tops of mountains and estimated the age of geological processes freely in periods of hundreds of thousands of years. He noted the effects of erosion on the shape of the earth's surface. He even noted the increase of erosion

through cultivation, now believed to be one of the causes of the decline of Graeco-Roman civilization.

"The rivers make greater deposits of soil when near to populated districts than they do where there are no inhabitants, because in such places the mountains and hills are being worked upon, and the rains wash away the soil that has been turned up more easily than the hard ground which is covered with weeds.

"The heights of mountains are more eternal and more enduring when they are covered with snow during the whole winter."

He noted the deeper colour of the blue sky seen from the top of Monte Rosa, and said: "The atmosphere acquires its blueness from the particles of moisture which catch the luminous rays of the sun."

"The blueness of smoke increases with the fineness of its particles. The whiteness of the smoke from burning wet green wood is due to the size of the particles, which are large enough to reflect light like a solid body."

Leonardo made sketches of apparatus for measuring the amount of steam produced by boiling a given quantity of water. He did not clearly distinguish between steam and air. This was first done properly by della Porta. He said that "whether air can be compressed in itself is shown by the barbers' vessel for supplying rose-water, in which it is doubled. Fire is quadrupled by the force of the place where it cannot increase." Leonardo's work was inspired by at least three motives: the desire for gain, for fame, and for knowledge.

His desire for gain is seen in his design and construction of machines for polishing needles. He writes that "early tomorrow, January 2nd, 1496, I shall make the leather belt and proceed to a trial." He calculates that "one hundred times in each hour 400 needles will be finished, making 40,000 in an hour and 480,000 in 12 hours. Suppose we say 4,000, which at 5 solidi per thousand gives 20,000 solidi; 1,000 lira per working

day, and if one works 20 days in the month, 60,000 ducats the year."

His desire for fame is seen in the concluding paragraph of his treatise on flight. The machine was to be launched from a mountain named the Great Swan, so he writes: "The great bird will take its first flight, on the back of its great swan, and filling the universe with stupor, filling all writings with its renown, and glory eternal to the nest where it was born."

His love of truth is seen in his observation that "though our spirit may have lying for its fifth element, nevertheless, the truth of things remains as the supreme nutriment for fine intelligences."

After describing the qualities desirable in a dissection, he says:

"As to whether all these things have been in me or no, the hundred and twenty books written by me will furnish sentence, yes or no, for in these I have not been hampered by avarice, or by negligence, but only by time. Vale."

Leonardo's great fertility in research has inspired discussions on his method of work. Paul Valéry has attributed to him a method of experimenting with concepts. He says: "It consists only in the throwing of one image—of one concrete mental relationship—amongst phenomena, amongst the images of phenomena, let us say, in order to be rigorous. Leonardo seems to have had knowledge of this kind of psychical experimentation, and it seems to me that during the three centuries after his death the method was recognized by nobody, though everyone used it—of necessity." He quotes Leonardo's meditations on rays of light: "The air is filled with an infinite number of straight and radiating lines, crossed and intercrossed, and never one of them coinciding with one another, and for each object they *represent* the true *Form* of their own reason." Valéry contends that "it was reserved for Faraday to rediscover the method of Leonardo as applied to physical science. . . . He, too, *visualized* systems of lines uniting all

bodies, filling all space in order to *explain* phenomena of electricity."

His comparison of the methods of Leonardo and Faraday is instructive, but did not the Ionian philosophers use the same method of experiment in the imagination when they developed the atomic theory? Usher has discussed the mental process of invention according to the principles of Gestalt psychology. He considers that invention occurs in perception and in conception. The primitive inventions in crafts are of the first sort. They consist of modifications of familiar operations that occur while the inventor is watching and handling his tools. Though these inventions may be of the greatest significance, after they are made they appear trivial to the spectator. This explains why the names of the inventors of fire, the wheel, and other fundamental primitive inventions are not remembered.

The other type of invention depends on experimenting with concepts in the imagination. When general laws of nature have been discovered, the conceptual inventor can invent in his imagination machines which obey these laws. He can sketch them on paper, and because they obey the laws they will work. Leonardo described this as "pre-imagining the imagining of things that are to be."

This achievement is very impressive, and when it becomes possible, inventors are admired and remembered, because they seem to be creating practical machines by mere imagination.

Edison's invention of the gramophone in twenty minutes is a notable illustration of experiment in the imagination with general scientific knowledge. Usher sees in Leonardo's work the transition from the perceptual to the conceptual mode of invention. His interesting and valuable discussion of invention before and after the creation of theoretical science helps to explain the difference in the degree of the fertility of primitive and modern invention, and gives one of the reasons why invention had less prestige in ancient than in modern times. But it does not explain why theoretical science was created. It can-

not be expected to explain a historical process, because it deals with psychological and not with historical concepts. History is explicable only in terms of theories of history and not in terms of theories of psychology.

Freud's interesting analysis of Leonardo's psychology has the same limitation. He has shown that his conduct and interests were probably fixed by special infantile experiences. He was an illegitimate child, and was reared by his mother alone until he was five. The absence of his father increased the acuteness of the normal infantile interest in his own origin, and established in him a powerful investigatory habit. His lonely mother's exaggerated affection produced in him sexual prematurity. He overcame this infantile excess by an energetic repression, and the repressed affection for his mother was expressed in idealized love for boys. The energy that would have been discharged in normal affections was sublimated through the investigatory habit, which was thereby deepened and made permanent.

Freud suggests that Leonardo was able to find in Ludovico Sforza a partial substitute for a father, and this explains the greater normality of his art during his period in Milan. When Sforza fell, and Leonardo had to leave him, he lost the substitute father who had unconsciously helped him to escape from his repressions. After this, the struggle against his repressions lapsed, and the amount of energy sublimated through the investigatory habit increased. Art was displaced still further by science, and was resumed only through the stimulation of profound infantile reminiscences. Freud suggests that the pictures of smiling women, such as "La Gioconda" and "St. Anne," painted by Leonardo in his later years, were due to the temporary release of his repressions through his meeting with women who appealed to his intense unconscious infantile reminiscences of his mother.

Freud's theory gives a plausible explanation of the origin of Leonardo's scientific habits and of his inhibitions. His in-

ability to complete paintings and to complete manuscripts for publication was related to the absence of completion in his sexual life, and the spread of repression from this part of his life into other parts. The extent of his scientific researches and their incompleteness are sublimations of his persistent search for, and failure to achieve, a normal sexual life.

This theory gives much insight into the features of his work and into his motives for investigating nature, but it does not explain why science had developed to the particular stage which gave special scope to a person with his peculiar psychology. A scientific discovery is immediately due to the interaction of two factors: the body of science and the mental characteristics of a scientist. The type of mind which can interact successfully with the body of science depends on the characteristics of the body of science at a particular epoch, and is different at different epochs. For instance, the body of science existing at the end of the nineteenth century was particularly suited for interaction with a mind like Rutherford's. His exceptional insight into the particulate aspects of phenomena might have been much less effective at other periods, when minds apt in other scientific conceptions could interact more successfully with the body of those classifications of scientific types for particular research-planning periods. If Rutherford had become mature in 1850, when the idea of vibration in continuous media was most fruitful, his discoveries might have been less important. Leonardo was fitted to advance science at the particular stage it had reached in his day. Progress was made then by working out numerous particular cases, and this came most easily to those with multifarious interests.

He was entirely emancipated from submission to authority. He said: "I do not understand how to quote as they do from learned authorities, but it is a much greater and more estimable matter to rely on experience, their masters' master."

He drew up rules for the description of the movements of

bodies, and tried to find mathematical statements for them. He said that "mechanics is the paradise of the mathematical sciences because by means of it one comes to the fruits of mathematics." Mechanics was valuable because mathematics became of social value through it, and it provided the way by which mathematics could become fertile in the investigation of nature. When a rule of mechanics had been discovered he said that "before making this case a general rule, test it by experiment two or three times, and see if the experience produces the same effect."

He had the three elements of the scientific method: observation, the reduction of the results of observation to mathematical rules, and the testing of these rules by experiment. The method was completed by his successors when they combined the three operations into one deliberate process.

Detailed knowledge of Leonardo's scientific researches has been acquired only during the last hundred years. One will ask how they could have had any influence on the history of science if they were not generally known soon after they had been made. His researches on human anatomy appear to have been entirely unread until recent times and to have had virtually no influence on the progress of science. It was thought for a long time that his researches on mechanics and mechanical invention had had little more effect, but historical research has recently shown that these manuscripts were read by a few able men who plagiarized from them without acknowledgment. Jerome Cardan was one of the most notable. The treatise on hydraulics published by Castelli in 1621 owed much to Leonardo's researches.

The treatments of the centre of gravity given by Villalpond, and of the centre of pressure by Baldi, were taken by them from Leonardo. They led to Huyghens' theory of centres of oscillation through Roberval, Descartes and Fabry. Many of Leonardo's discoveries and inventions in mechanics had filtered anonymously into the body of mechanical knowledge

at the beginning of the seventeenth century. Though the belief that Leonardo's mechanical researches had little influence is untrue, the inefficiency of the publication of his work is evident. This was not entirely due to his faults. The new technique of printing was developed during his lifetime, and the circulation of manuscripts was still the chief method of spreading knowledge. Many of the leading patrons of learning in the fifteenth century regarded printed books as vulgar and would not have them in their libraries. The printed book democratized learning and was as distasteful to many aristocrats then as the gramophone and the cinema have been to contemporary cultural aristocrats.

Leonardo himself esteemed printing very highly, and intended to print his notebooks, but his failure to do so had less serious effect in his lifetime than afterwards, when printing became the usual mode of publication.

The absence of scientific societies and scientific journals contributed much to the inefficiency of the publication of Leonardo's researches. Great discoverers are often averse to publication. The most famous example is Newton. Fortunately, there was a group of scientists who tactfully persuaded him to publish an account of his discoveries. There was no similar group to overcome Leonardo's hesitations. Failure to publish is not due entirely to the discoverer; it may also be due to the absence of necessary social mechanism.

Newton's *Principia* was published at Halley's expense. The cost of publishing Leonardo's notebooks would have been large. One of the inheritors of the notebooks attempted to arrange for publication, but could not secure sufficient financial aid. It was in fact impracticable without the aid of a scientific society, and one may deduce that the non-publication of his work was chiefly due to the contemporary social organization. If a scientific journal had existed, Leonardo could conveniently have published his researches in a long series of short papers.

The incompleteness of his researches was connected with the absence of organized research laboratories. These were evolved after the factory system had developed, and owe much to it. Disciplined research workers, whose habits had been learned from the factory, would have enabled him to complete his investigations. He would then have expressed the laws of mechanics in the perfect modern form. He could not do this because the systematization of work, and hence of thought, had not proceeded far enough in the workshop of the arist and craftsman. A century later, the statement of the general laws of mechanics became easier, because the organization of work had evolved further towards the factory system, and systematic thinking became more habitual. Leonardo's inability to complete his researches was not due merely to psychological peculiarities. It was perhaps due, even more, to the particular nature of the contemporary mode of craft production, which was very individualistic.

When Leonardo's inventions and discoveries are summarized, they give an impression of extraordinary originality, but when they are seen against the five thousand pages of his notebooks, they appear in more correct relief. The bulk of Leonardo's work was not original. He was widely read. Seventy-two medieval and classical authors are quoted by him, and he was familiar with the medieval researches summarized in Section 43. He had read Albert of Saxony on gravitation, Jordanus on levers, and Roger Bacon on optics and flight. He had read Vitruvius, and sought translations of Archimedes. He was acquainted with Argyropoulos, the Greek scholar who translated Aristotle's *Physica* and *De Coelo* into Italian. He knew the writings of the great architect Alberti, who had improved the camera obscura, measured the depth of sea beds, invented a hygrometer and developed marine salvage. He collaborated with the architect Bramante, and met students of Aristotle, Aricenna and Averroes. He was friendly with della Torre, the professor of anatomy at Pavia. He read the works of Alkindi

and Alhazen. The mathematician Pacioli, who was appointed to a chair of mathematics at Milan and accompanied him when he left Milan, was one of his best friends. Pacioli wrote the first textbook on arithmetic and algebra that was printed. It was published in 1494, and was based on the thirteenth-century treatise by Leonardo of Pisa. Leonardo drew the diagrams for another treatise by Pacioli, which was on proportion. Leonardo also knew Toscanelli, who in 1474 had enthusiastically encouraged Columbus to sail to the west.

Leonardo was not a good linguist, and wrote in the style of a Florentine bourgeois. He could read Latin, but not Greek. There is little doubt that most of his mechanical inventions were improvements on machines he had seen or heard of, and his scientific discoveries were extensions of the researches of his medieval predecessors. His original contributions appear as a series of normal peaks on a high plateau of old knowledge.

The most striking feature of his work, viewed as a whole, is its mark of experimental labour. It is evident that manual labour had become reputable. Leonardo continually praises labour. When Vasari tried to explain why art had flourished so brilliantly in Florence, he ascribed it to three things. "The first is censure, which is uttered freely and by many, seeing that the air of that city makes men's intellects so free by nature that they do not content themselves, like a flock of sheep, with mediocre works, but ever consider them with regard to the honour of the good and the beautiful, rather than out of respect for the craftsman. The second is that, if a man wishes to live there, he must be industrious, which is naught else than to say that he must continually exercise his intelligence and his judgment, must be ready and adroit in his affairs, and, finally, must know how to make money, seeing that the territory of Florence is not so wide or abundant as to enable her to support at little cost all who live there, as can be done in countries rich enough. The third, which perchance is no less potent than the others, is an eager desire for glory and honour, which is generated

mightily by that air in the men of all professions; and this desire, in all persons of spirit, will not let them stay content with being equal, much less inferior, to those whom they see to be men like themselves, although they may recognize them as masters—nay, it forces them often to desire their own advancement. So eagerly, that if they are not kindly or wise by nature, they turn out evil speakers, ungrateful, and unthankful for benefits. It is true, indeed, that when a man has learnt there as much as suffices for him, he must, if he wishes to do more than live from day to day like an animal, and desires to become rich, take his departure from that place and find a sale abroad for the excellence of his works and for the repute conferred on him by that city, as the doctors do with the fame derived from their studies. For Florence treats her craftsmen as time treats its own works, which, when perfected, it destroys and consumes little by little."

In this explanation it is clear that the social prestige of the craftsman had become established in a mercantile society. Manual work and experimental science owe much of their social emancipation from slavery and serfdom to the rise of the repute of the craftsman at the transition from medieval to Renaissance society.

Vasari has described the conditions in Donatello's workshop. "He was most liberal, gracious and courteous, and more careful for his friends than for himself; nor did he give thought to money, but kept his in a basket suspended by a cord from the ceiling, wherefore all his workmen and friends could take what they needed without saying a word to him."

The social stigma of manual work, which had so long inhibited experimental science, had disappeared. The Medici, and the new ruling class of moneyed men, had undermined the feudal castes, and the depressed industrial proletariat had not yet evolved. The revolutionary vigour of the Medici and their class soon declined after they had seized power, and they advocated a Platonic culture suitable to a class of ruling

bankers. This was inimical to science, but craftsmen, whose work had been essential to merchants and exporters of luxuries, had been released from social subjection during the transference of power from feudal lords to bankers. The establishment of the social repute of craftsmen created the condition in which experimental science could grow.

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THE SEARCH FOR PRECIOUS METALS

The evolution of a new type of society based on commerce, money and credit proceeded steadily until the fourteenth century. The organization of the old medieval society weakened as the new system grew. This process of disorganization was accelerated by constant wars, and by the epidemic Black Death, which killed about half of the population in the middle of the fourteenth century. The long wars between England and France had a particularly disturbing effect. They interrupted the trade route through France between Flanders and Italy. The raw cloth woven from English wool in Flanders could no longer be safely transported through France to Florence for finishing, and the Italian merchants could not safely travel through France to Flanders to supervise the management of the commercial side of the trade. The Italian and Flemish merchants diverted their route to the Rhine, and converted it into the highway of Europe. This founded the prosperity of the south German towns such as Augsburg and Nürnberg. The dangerous conditions stimulated the use of bills of exchange to avoid the transport of money. The devastation of the French towns weakened the commercial initiative of the French bourgeoisie. It looked to the king for help, and he exerted his aid through his own centralized authority. French industry and commerce became organized on national rather than civic lines, and the king's financial advisers acquired great power and riches. These men enabled him to raise funds without consulting any class in society. Jacques Cœur was one of a group which leased the minting of money from Charles VII.

He learned the nature of the trade in metals, and in 1432 began to export silver to the East, and import gold, which he sold in France at an enormous profit. He leased the Crown's mines in France, and engaged German miners to work them. He lent money to the French court at interests of 12 to 50 per cent. Though he was extortionate, he provided the king with the funds, and established regular taxes on trade, industry and agriculture, which enabled him to create the first regular army in 1439. Cœur left a fortune equivalent to about one million pounds in gold. And yet during his period the total volume of trade in France had not greatly increased. His accumulation was due to a transference of wealth from other members of society to himself.

The merchants in the south German towns profited from the diversion of trade to their cities. In Augsburg at the end of the fourteenth century two merchants named Fugger, who were the sons of a cloth dealer, began to import cotton from Venice for finishing, and learned the principles of commerce from the Italians. Jacob, one of their sons, became master of the weavers' guild, and had seven sons. One of these sons, named Ulrich, engaged in international finance, and exported works by Dürer to Italy. Ulrich recalled his brother Jacob II from a theological college to work in the business. Jacob II proved the greatest of the family's financiers. Jacob II engaged in mining, and formed a partnership in 1505 with Hochstadter and Welser, to import three cargoes of goods direct to Germany from India by the route newly discovered by Vasco da Gama.

Hochstadter borrowed the savings of the people and paid the depositors five per cent interest. He speculated with the deposits and became a monopolist of wood, corn, wine, copper and mercury, but ultimately failed.

The commerce between Europe and Asia was conducted by the export of silver, and the increasing scarcity of the precious metal produced a steady fall in prices, which was bad for trade. The Fuggers transferred more of their attention to

the precious metals to obtain ingots and money as security for lending. They encouraged prospecting and the development of the metal mines in the Tyrol, Bohemia and Hungary, and began to mine silver in 1487. They engaged in copper mining in Hungary ten years later, and cornered the copper market in Venice.

The supply of silver and other metals in Europe was considerably increased by this activity. German capitalists who had acquired wealth in trade entered many departments of the metallurgical industry, and Nürnberg capitalists established iron forges in Thuringia. Europe's supply of gold, and the spices necessary for seasoning food before the discovery of methods of preservation, came through Islam.

The Western Europeans aspired in the early Middle Ages to evade Islam and attack it in the rear by finding a direct route to the Indies, and a Genoese expedition led by the Dorias tried to discover the route around Africa in 1291. Genoese captains discovered the Canaries and Madeira. The mariners who explored the Atlantic coast of Africa returned with new knowledge, which they incorporated in charts free from the fancies of scholars. Their charts, which were simply guides to practice, were neglected by the theoretical scientists of the fifteenth and sixteenth centuries. The Portuguese became interested in the expeditions beyond their shores, and, about 1350, members of the royal house began to collect the new geographical knowledge and study the technique of navigation. One of them acquired an original copy of Marco Polo's narrative and a valuable map in Venice.

An expedition was sent from Lisbon in 1341 to search for western islands in the Atlantic. An Italian map was prepared in 1351, which apparently incorporated its results and gave a remarkably exact forecast of the shape of Africa.

The Portuguese studies were continued by Prince Henry the Navigator. His father was King John I of Portugal and his mother was Philippa, the daughter of John of Gaunt. He was

born in 1394 and distinguished himself at the capture of Ceuta from the Moors in 1415. Before King John died in 1433, he exhorted his son to accomplish the efforts to round Cape Bojador. Henry's captains brought the first slaves and gold dust from the Guinea coast beyond Bojador in 1441, and aroused boundless hopes of profit from geographical discovery.

Henry engaged Jacome of Majorca, and Arab and Jewish mathematicians to teach the rules of astronomy and the use of instruments to his navigators. He established an observatory at Sagres, near Cape St. Vincent, to make more accurate tables of the declination of the sun. His caravels or frigates were reputed the best sailing vessels afloat. Their seaworthiness and technical quality were essential for the success of the long coastal voyages.

Henry died in 1460. His work was extended by King John II, who employed his physicians Roderick and Joseph, and Martin of Bohemia as his committee on navigation. They calculated tables of the sun's declination, and improved the astrolabe, which he recommended as more convenient than the cross staff for observing the sun's declination.

The Spanish appointed a committee at this time for the instruction of pilots for voyages to the Indies. A record of their course exists. It was based on Sacrobosco's treatise on the sphere, Regiomontanus' spherical trigonometry and Ptolemy's *Almagest;* with exercises in the use of instruments and the observation of the movements of the heavenly bodies, and cartography. Regiomontanus' treatise was the first modern exposition of trigonometry, and was written in 1464. In it he used the sine and cosine, and applied algebra to the solution of geometrical problems. He was born at Königsberg in 1436, and his original name was Johannes Müller. He settled at Nürnberg in 1471, which was then a centre of trade and finance. He was invited by the Pope to reform the calendar and died in 1476 shortly after his arrival in Rome. The methods of determining position at land, which had been developed consider-

ably in antiquity, were applied very slowly to navigation. The difficulty of making observations on a moving platform was great, and the need for scientific navigation in the narrow Mediterranean sea was not imperative. The Muslims and the Chinese could cross the Indian and the China seas by following the monsoons, which blew very steadily in known directions.

When the desire for gold urged mariners to cross the Atlantic, they had to devise improved technique to deal with the more difficult conditions. A Portuguese writer of the fifteenth century said: "Our discoveries of coasts and islands and mainland were not made without foresight and knowledge. For our sailors went out very well taught, and furnished with instruments and rules of astrology and geometry, things which all mariners and map-makers must know."

Christopher Columbus was born in 1446 in Genoa. His father was a wool-comber and he became a weaver before going to sea. As a mariner he visited England, and claimed to have been in Iceland in 1477. He became virtually Spanish and in 1478 married a daughter of one of the officers of Henry the Navigator. He studied his father-in-law's maps, and meditated on the possibility of reaching India by sailing westwards.

He prepared plans for a westward voyage based on the shape of the earth, the theories of geographers, and the rumours of mariners. His conception of the shape of the earth was innaccurate. He wrote in a letter to Isabella in 1498, after his discovery, that "the old Hemisphere has for its centre the isle of Arim, is spherical, but the other [new] Hemisphere has the form of the lower half of a pear. Just one hundred leagues west of the Azores the earth rises at the Equator and the temperature grows keener. The summit is over against the mouth of the Orinoco."

The conception that the earth comes to a peak at Arim is Muslim. The attribution of the pear-shape implied that the Pacific Ocean would be small. He underestimated the size of the world and overestimated the size of Asia. This defective

mixture of Ptolemaic and Muslim geography gave him false evidence for the ease of the western voyage to India.

He had heard that mariners had seen strange wood and canes in the western Atlantic, and if he had visited Iceland he may have heard of Leif Ericson's voyages.

He presented his plan to King John II of Portugal, who was keenly interested in the rival plan to reach India by a coastal route round Africa. The Bishop of Ceuta ingeniously suggested that Columbus' plan should be tried without his knowledge. A ship was accordingly sent to the west in secret, but it returned without success. The plan was offered to the court of France, and to Queen Isabella in 1486. Columbus' hopes were strengthened by Diaz's discovery of the Cape of Good Hope in 1488 and he sent his brother Bartholomew to England to try to interest Henry VII in his plan, but without success. Bartholomew tried again at the French court, but in the meantime, Ferdinand and Isabella had achieved success in their campaign to expel the Moors, and had time to receive Columbus again. He offered to lead an expedition to the west on the condition that he be appointed to the rank of admiral "in all those islands, seas and continents that he might discover, the vice-royalty of all he should discover and a tenth of the precious metals discovered within his admiralty." This condition was rejected, and he left for the court of France; Ferdinand and Isabella immediately changed their minds, and sent a messenger to bring him back, reaching him when he was six miles from Granada. He returned to the camp at Santa Fé, and signed the agreement on April 17, 1492. He sailed on August 3, 1492. On September 13 the western variations of the magnetic needle were observed for the first time. This frightened the crew. On October 12, 1492, one of his sailors sighted the New World.

Columbus collected specimens of slaves and gold, and sailed back to Europe, anchoring off Lisbon on March 4, 1493. Alex-

ander Borgia, the Pope, issued bulls confirming the possession of all lands west of the Azores to Spain, as the African colonies had previously been allotted to Portugal. Columbus founded the West Indian slave trade on February 2, 1494, and established mining camps for gold on Haiti. Like so many men in the new commercial society, he hungered for gold. He said: "Gold is the greatest earthly good. Its possessor can do as he will, even to despatching souls to paradise."

He found the natives of Haiti gentle, upright and simple. When they resisted enslavement and fled, he hunted them with blood-hounds. Burney remarked that "a man-hunt with blood-hounds was an unheard-of atrocity before Christopher Columbus invented it. It is more barbarous than cannibalism." One-third of the population of Haiti died in a few months. He had difficulties with his own men, and seven of them died under his tortures. News of these disorders reached the Spanish court, and an officer named Bobadilla was sent to Haiti to supersede him. Bobadilla put Columbus and his brothers in chains and sent them back to Spain. Columbus insisted on wearing them throughout the voyage "as relics and as memorials of the reward of his service." His son said that he "saw them always hanging in his cabinets, and he requested that when he died they might be buried with him."

The Spanish court had, however, been justifiably shocked by his cruelty and avarice. It had been agreed that the seaman who first sighted land should receive a pension of ten thousand pieces of money. Columbus claimed this for himself, although he was not the first.

On his second voyage he suffered from nervous prostration through excessive exertion, and when he returned to Europe he was wearing the garb of the Franciscans, the friars who took the vow of poverty.

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52

METAL MINING

The increasing demand in the fifteenth century for precious metals for coining, and for silver to pay for imports from the East, stimulated mining. The south German merchants, who were profiting from the Flemish-Italian trade, encouraged prospecting in the German mountains, and by the end of the century the requirements of the Fuggers and others had created a mining boom. This was accompanied by a big improvement in technique.

As slavery had declined, one direction of this improvement was in appliances for saving labour.

Small notebooks on mining appeared at the beginning of the sixteenth century. These were written by practical men to refresh the memories of miners and metallurgists and were not textbooks. The earliest known, *Ein Nutzlich Berg Buchlein*, was probably published at Augsburg in 1505. Another, named the *Probier Buchlein*, was published about 1510. These soon passed through several editions.

The Italian Biringuccio published a work at Venice in 1540 which contains the first printed account of the mercury process for extracting silver, the reverberatory furnace, and the liquation process, by which silver is separated from copper by keeping the temperature of the melt below the melting point of copper and about that of silver. He also appears to be the first to mention cobalt blue and manganese.

These were slight predecessors for the description of the systematization and improvement of mining technique accomplished in Germany in the fifteenth century and splendidly

recorded in Agricola's Latin treatise on metals. An admirable annotated English translation has been made by Herbert C. Hoover and his wife, Lou H. Hoover.

Agricola was born in Saxony, near the Erzgebirge, or Ore Mountain, in 1494. His original German name was Georg Bauer. He graduated at Leipzig University and was appointed to the municipal school at Zwickau, near his home, in 1518. He became principal in 1520, having as one of his assistants Johannes Forster, who collaborated with Luther on the translation of the Bible. He published in the same year his first book, which was a small Latin grammar. He left Zwickau in 1522, to lecture under his friend Mosellanus at Leipzig University. When Mosellanus died in 1524, Agricola went to Italy at the age of thirty to advance his studies, and remained there about three years. Like Copernicus, Harvey and many other northern European scientists of the period, his scientific inspiration and education was Italian, as he first began to concentrate on science while visiting the universities of Bologna, Venice and Padua. He specialized in medicine and began a revision of Galen. He became acquainted with Erasmus, who had settled at Basel as editor for Froben's press.

He returned to Zwickau in 1526, and in 1527 was chosen town physician at Joachimsthal, a booming mining camp founded only eleven years before that already had a population of several thousands. Joachimsthal was in the midst of the Erzgebirge mining district, and within fifty miles of Freiberg, Schneeberg, Geyer, Altenberg and Annaberg and other well-known mining towns. When Elizabeth was improving British mining in 1565, she granted a patent to William Humfrey, paymaster of the Mint, to bring to England "one Christopher Shutz, an Almain born at St. Annen Berg"; a workman of "great cunning" in finding and working calamin stone (zinc ore).

Agricola spent all of his time not devoted to medical duties in visiting mines and smelters, and reading all references to min-

ing in Greek and Latin authors. He learned mining technique from skilled miners, and cast one of them, named Bermann, as a speaker in a dialogue he composed on mining and mineralogy. This dialogue was published under the title *Bermannus* by Froben in 1530, with a laudatory preface by Erasmus.

His mining knowledge now became profitable, for he acquired shares in the God's Gift mine at Albertham, discovered in 1530, which proved very rich. He wrote in 1545 that "we, as a shareholder, through the goodness of God, have enjoyed the proceeds of this God's Gift since the very time when the mine began first to bestow such riches."

His income from this mine seems to have enabled him to retire for a time from medicine, for he resigned from his post as town physician of Joachimsthal in 1530, and appears to have spent the whole of his time in visiting and studying mines. He was appointed city physician at Chemnitz in 1533, and resided there until 1555. He continued to have much time for mining. He published the first systematic works on physical geology and on mineralogy and both of these contributions to science were derived from his mining knowledge.

Agricola was a Catholic and retained his views through the Reformation, though he lived in the midst of an enthusiastically Protestant population. The social and religious conceptions of the miners were expressed by Protestantism better than by Catholicism, which was more suited to the southern European agricultural population. In fact, the energy generated by the expanded German mining industry was an important motive of the Reformation.

In spite of his Catholicism, Agricola was promoted by Protestant princes. He was appointed Burgomaster of Chemnitz in 1546 by the Elector Maurice of Saxony, who, though a Protestant, collaborated with the Spanish Holy Roman Emperor Charles V against the league of German Protestant princes. The actions of Agricola and Maurice against their respective religious interests were probably due to the overriding influ-

ence of economic motives. The chief patrons of the German miners were the Fuggers, who were Charles V's financial managers, so there were powerful reasons for finding an accommodation with the Catholic Emperor.

Agricola was a liberal Catholic who shared Erasmus' attitude. Like him, he was tactful, profound and competent, but was following a dwindling minority. He behaved with discretion in religious matters, so the Protestant mine-owners ignored his religious opinions but made use of his expert knowledge. His views on class-conflicts were sound, for he writes of mining disputes that "I always find that the owners who are abused have the best reasons for driving the men from the mines."

Agricola spent twenty-five years collecting material for his treatise on metals. The text was completed in 1550, but five years passed before the illustrations were completed. These are one of the treasures of knowledge, for they are explanatory pictures of the contemporary methods and equipment of mining. Agricola was aware of the limitations of verbal descriptions of machinery, and he specifically expended so much expense and care on the illustrations for the benefit of posterity, who would be able to see at a glance from them the construction of machines. They have also provided an invaluable picture of the contemporary miners' mode of life, with its social implications. The printing had not been completed when he died in 1555, and the treatise was published in the following year.

Agricola starts his work with an apology for mining. One set of critics say that "scarcely one in a hundred who dig metals or other such things derives profits therefrom." He answers this by asserting that the majority of miners are unskilled. They are men "weighted with the fetters of large and heavy debts, they have abandoned a business, or desiring to change their occupation, have left the reaping-hook and plough." As they are ignorant, they do not know how to find good veins and work them efficiently.

He replies to those who condemn tne instability of mining as compared with agriculture that the gold and silver mines belonging to the communities of Chemnitz have been worked for eight hundred years, and "are said to be the most ancient privileges of the inhabitants." Though he does not wish to "detract anything from the dignity of agriculture," he explains that "the yearly profit of a lead mine in comparison with the fruitfulness of the best fields is three times or at least twice as great."

To those critics who condemn mining because "the miners are sometimes killed by the pestilential air which they breathe; sometimes their lungs rot away; sometimes the men perish by being crushed in by masses of rock; sometimes, falling from the ladders into the shafts, they break their arms, legs or necks," and who assert that no compensation is sufficient for such dangers and loss of life, he replies that while he confesses that these occurrences are of exceeding gravity and, moreover, fraught with terror and peril, so that he would consider that metals should not be mined at all if they were frequent, "things like this rarely happen, and only in so far as workmen are careless."

He admits that mining destroys good agricultural land and forests and mentions an Italian law against mining for the protection of fertile fields. But he explains that mining is usually prosecuted in mountains unsuited to agriculture.

He admits that iron and bronze have increased the destructiveness of armaments, and gold has stimulated robbery, but the standard of civil life has been raised immeasurably by metal tools and machinery.

Finally, "The metals are useful to merchants with very great cause, for, as I have stated elsewhere, the use of money which is made from metals is much more convenient to mankind than the old system of exchange of commodities [barter]."

He then discusses the repute of mining, and whether it is "honourable employment for respectable people." He contends that while in the past it might have been dishonourable because miners were convicts and slaves, they are now free

men, and "receive pay, and are engaged like other workmen in the common trades." Indeed, "it would not be unseemly for the owners themselves to work with their own hands on the works or ore, especially if they themselves have contributed to the cost of mines." The mine-owner should sometimes "undertake actual labour, not thereby demeaning himself, but in order to encourage his workmen by his own diligence." Manual work has become reputable even for owners.

Some men say "that the scum of the miners exist wholly by fraud, deceit, and lying. For to speak of nothing else, but only of those deceits which are practiced in buying and selling, it is said that they either advertise the veins with false and imaginary praises, so that they can sell the shares in the mines at one-half more than they are worth, or on the contrary, they sometimes detract from the estimate of them so that they can buy shares for a small price."

As for such frauds, Agricola says, "I concede it. But can they deceive anyone except a stupid, careless man, unskilled in mining matters?" He says that "the miners themselves rarely buy or sell shares, but generally they have brokers who buy and sell at such prices as they have been instructed to give or accept."

He starts his technical discussions with advice on prospecting. Clusters of wooded mountains are the most promising. If there is no forest for the supply of timber, then parts of the mountains near rivers, on which timber may be transported, should be chosen.

Low-lying plains should be avoided, owing to the difficulties of drainage and ventilation and the construction of shafts. Gently sloping tunnels may be driven into the sides of mountains, and gravitation will assist the drainage of water and the transport of ore from the working places to the exterior. The presence of veins may be detected from the flavour of springs by the warmth which liquefies hoar frost on their surface, by exhalations, and other signs. He gives a careful and illustrated

account of the divining rod, and says that "it ought to be examined on its own merits." He explains that the movements of a forked twig are more difficult to follow than those of a straight twig. Cunning persons twist the twig, and simple ones move it involuntarily owing to the peculiar way in which they hold it. For these and other clearly expressed reasons, a miner "if he is prudent and skilled in the natural signs, understands that a forked stick is of no use to him."

He suggests that "the divining rod passed to the mines from its impure origin with the magicians," who used divining rods and incantations. "When good men shrank with horror from the incantations and rejected them, the twig was retained by the unsophisticated common miners, and in searching for new veins some traces of these ancient usages remain."

Robert Boyle, one century later, believed firmly in dowsing. His credulity was no doubt due to less direct experience of mineral prospecting.

Agricola generally shows a very high standard of clarity and material rationalism in explanation, derived from intense study of mining processes. Yet even he believed in mine demons. Hoover remarks that the widespread belief of miners in demons is due to the environment. He says, "Neither the sea nor the forest so lends itself to the substantiation of the supernatural as does the mine. The dead darkness in which the miners' lamps serve only to distort every shape, the uncanny noises of restless rocks whose support has been undermined, the approach of danger and death without warning, the sudden vanishing or discovery of good fortune, all yield a thousand corroborations to minds long steeped in ignorance and prepared for the miraculous through religious teaching."

The vertical and horizontal distribution of veins is described, and an account of the strata in the copper-bearing Harz mountains contains the first attempt at stratigraphic distinctions. Twenty strata are identified. The methods of forecasting the directions of strata are explained. These enable a miner to de-

duce the position of veins on his property from the known positions of veins on his neighbour's properties.

In another work, he gives the first satisfactory explanation of the origin of ore veins. He suggests that they are the sites of cracks and faults in the original rocks, which have been filled by deposition from waters and solutions circulating underground. This is the foundation of modern theory, and was expressed by Agricola more clearly than by any of his successors for two centuries.

He enumerated the sixty species of minerals already recognized, and added twenty new ores to the list. He was the first to assert that antimony and bismuth are metals.

He described the formation of mountains by erosion more fully and clearly than his predecessors.

He gave the first adequate account of the complicated methods and chemistry of assaying. His illustrations of furnaces show the degree of the advance in their design, and the numerous instruments used in conjunction with them. The products of the chemical analyses were weighed in balances protected from draughts, whose beams could be raised by a pulley for the moment of weighing, and then lowered until the pans rested on the base, so that the knife-edges were relieved from pressure when not in use.

Hoover states that his account of the assaying of lead, copper, tin, quicksilver, iron, and bismuth, and his explanation of the corresponding chemistry, is almost wholly new, and he would like to "call the attention of students of the history of chemistry to the general oversight of these early sixteenth-century attempts at analytical chemistry, for in them lie the foundations of that science."

His illustrations show numerous wheelbarrows. These look as if they had evolved from a hand-barrow carried by two men, through the substitution of a wheel for one man. The design of the supports for the axle of the wheel still resembles in shape the handles from which it was derived. This shows

that the wheelbarrow was invented to increase the amount of ore that could be carried by a given number of labourers, rather than to reduce the amount of labour falling on each man.

A four-wheeled truck, with "a capacity half as large again as a wheelbarrow" is described with a picture. "A large blunt pin fixed to the bottom of the truck runs in a groove of a plank in such a way that the truck does not leave the beaten track. Holding the back part with his hands, the carrier pushes out the truck laden with excavated material, and pushes it back again empty. Some people call it a 'dog,' because when it moves it makes a noise which seems to them not unlike the bark of a dog. This truck is used when they draw loads out of the longest tunnels, both because it is moved more easily and because a heavier load can be placed in it."

The first known illustration of a mining truck running on rails was given by Munster in 1550. Wooden railroads had probably been in use in German mines for some time.

Agricola mentions that men worked in seven-hour shifts, with one hour for walking in and out of the workings. They were not supposed to work more than one shift in succession, as they were liable to fall asleep on the second shift, or slip off home before the end of the second shift. If they had to work double shifts to deal with flooding or other accidents, "to prevent themselves falling asleep from the late hours or from fatigue, they lighten their long and arduous labours by singing, which is neither wholly untrained nor unpleasing."

As Agricola expresses it, the miner is allowed to work two shifts a day in some districts "because he cannot subsist on the pay of one shift, especially if provisions grow dearer."

The problems of ventilation are described, and the seasonal variation in the direction of the natural draught through the workings is noted. The inward draught is increased by ventilators that can be turned to catch the wind, and various designs of fans driven by hand, or by water wheels or windmills.

Large bellows are applied to the same purpose. These are

also used for sucking bad air out of workings as much as twelve hundred feet long. He says that "if machines of this kind had not been invented, it would be necessary for miners to drive two tunnels into a mountain" and "this could not be done without great expense."

Agricola's descriptions and illustrations of hauling machines and pumps are particularly striking. He said that "the depths of our shafts forced us to invent hauling machines suitable for them." He depicts a large reversible winch driven by a water-wheel thirty-six feet in diameter. This machine requires five operations. The wheel contains two parallel sets of buckets with two movable troughs. The direction of rotation is controlled by an operator who raises or lowers the appropriate trough.

He depicts powerful rag-and-chain pumps which would raise water 220 feet and were used at Chemnitz to raise water 660 feet in three stages. These consisted of a chain with leather balls spaced at distances of six feet. As the chain was pulled through the pipe, the balls acted as primitive pistons and pushed the water before them. He gives a picture of a heavy chain of dippers rotated through gearing of the clock type, and the end bearing the heavy chain resting on a steel roller bearing.

He described seven species of suction pump. These were made from hollowed trunks, and their pistons were lifted directly by a labourer, or operated by water-wheels through cams.

"The seventh kind of pump, invented ten years ago, which is the most ingenious, durable, and useful of all, can be made without much expense."

It consisted of a series of suction pumps. The inlet holes of the lowest pump were in the sump at the bottom of the mine, and the pumped water was delivered into an elevated tank. This acted as the sump for the second pump, and so on. All of these pumps were driven simultaneously by a water-wheel through a system of links.

These multiple-stage suction pumps evaded the problem of pressure raised by force pumps. It was possible to design force pumps that would theoretically raise water one thousand feet, but the wooden pipes which would have been used for carrying the water would not have stood the resulting pressures.

Experience vividly proved that water could not be raised more than a limited distance by one suction pump. Agricola says that it may raise water "as much as twenty-four feet."

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53

THE EFFECTS OF AMERICAN GOLD

The Italian Renaissance drew its strength from the stream of European commerce, which had been created by the Italians and converged in their country. At the time when the Renaissance was receiving its greatest expression, in the works of Machiavelli and Leonardo da Vinci, the decline of the commercial movement that fed it had already begun, and this was accelerated disastrously by the discovery of America.

The Augsburg merchants had noticed some time before that Atlantic navigation was damaging the Rhine trade route, and one eminent German merchant emigrated to Antwerp in 1474. The Venetian trade was declining, Genoa monopolized the wool trade, and Florence was cultivating a new southern trade with Morocco.

The Portuguese who had opened the direct trade with the East were too busy conducting the long voyage to attend to the distribution of their cargoes. These were reshipped from Lisbon to Antwerp, where the regulations for commerce were exceptionally free. Antwerp had antagonized the older towns by taking some of their trade, and was forced to develop on its own lines in self-defence. As it had long had a fair, it concentrated on this institution and made it continuous, so that the city could specialize in commerce. The older towns, with their intricate medieval regulations aiming at the exploitation of a small fixed market, were unfitted to deal with sudden changes in volume of business due to the change of trade routes. Antwerp specialized in this commerce that other cities did not like and could not undertake. The German merchants, who had formerly imported goods through their offices in

Venice, now established their houses in Antwerp, which became the centre for the distribution of the new ocean trade in gold, silver and spices.

The city became the greatest in Europe, and its great wholesale trade inspired improvements in the technique of commerce, such as the invention of commission business and the modern bourse. The occasional fair is characteristic of medieval economy. The word "bourse" comes from the name of the square in Bruges where the Florentine, Genoese and Venetian merchants had offices.

These developments required a new accuracy in standardization before merchants could confidently deal in goods without seeing them.

America was owned by the Spaniards, and the unprecedented quantities of gold and silver found there belonged to them. The Spanish monarchy engaged the Fuggers and other capitalists to manage the business. Gold was collected in the West Indies until 1516. Production in Mexico started in 1522, and in Peru in 1533.

The method of extraction with mercury was introduced in America in 1557. This greatly enhanced the value of the mercury mines at Almaden in Spain. The exploitation of these mines was entrusted to the Fuggers, who also formed settlements in Peru and connections in various parts of America. The Welsers were allowed to mine copper in San Domingo.

The Spanish colonists in America devoted themselves almost entirely to mining. They imported their food from Spain. This produced a rise in the price of food in Spain which hurt the people. The development of manufacture was neglected, and the imports of foreign manufactures, and even food, increased.

A Venetian ambassador reported that "the Spaniard can only live through France. Hence he must import corn, textiles, paper, books, even to carpenters' work, and must himself travel to the ends of the earth for gold to pay for them."

The transport of the Spanish and Portuguese cargoes from the Indies from Lisbon to Antwerp was undertaken by Dutch fishermen. They returned to the Iberian peninsula with cargoes of salt-fish and cloth.

As the Spanish trusted to their supplies of gold, and neglected to cultivate their own agriculture and industry, they depended almost entirely on foreign countries for high-grade manufactured goods. According to Bodin, they exported one hundred million pounds of gold, and two hundred million pounds of silver to France after 1533, which were enormous quantities at that time. It produced a great fall in prices, and after the opening of the mines at Potosi in 1545, the fall was catastrophic. Feudal rents lost four-fifths of their value, charitable foundations, hospitals and schools were ruined, and the middle class bought many estates.

As financiers to the Spanish crown, the Fuggers drew immense profits. They lent Charles V 310,000 florins to outbid Francis I of France for the title of Holy Roman Emperor. Charles pledged to them the whole of Antwerp, the greatest city in the world, as security.

The Spanish policy collapsed when the supply of gold from America began to contract. It left Spain without any permanent inheritance of improvement and skill. Philip II went bankrupt in 1575 and 1596. This crippled the Fuggers and other German and Genoese bankers, and afterwards the private capitalists no longer looked to the financing of kings' wars and policies for their largest profits.

The Spaniards turned on Antwerp and destroyed it in 1576, but they could not destroy the technical knowledge acquired by the Flemings. This became the foundation of the achievements of Stevin and Huyghens.

The wealth of the Spaniards passed to the Dutch, who were their bitterest enemies.

54

WILLIAM THE SILENT'S QUARTERMASTER GENERAL

The concentration of world commerce in the Netherlands put an excessive burden on the local merchants. Their more intelligent members were impelled to seek quicker and simpler methods of calculation, which would save the labour of clerks and increase the turnover of business. In response to this situation, Simon Stevin, who was born at Bruges in 1548 and died at The Hague in 1620, invented the decimal system. He was unaware that he had rediscovered a method of the Babylonians, or that some others had previously made partial use of the idea of a decimal. He wrote the first treatise on decimals. This was published in Flemish and French in 1585. An English translation was made by Robert Norton in 1608. Norton's title is *Disme: the Art of Tenths; or Decimall Arithmetike.* Stevin salutes his public in the preface. He writes: "To Astronomers, Land-meaters, Measurers of Tapistry, Gaudgers, Stereometers in generall, Money-Masters, and to all Marchants, Simon Stevin wisheth health."

He excuses his presumption in offering such a small book, which contains only a couple of dozen pages, to so many worthy people, asking them to reflect that they should not measure the merit of the book by comparison with their own great worthiness, but by comparison with "human imbecility."

"But what of that?" he asks. "Is this an admirable invention? No certainly: for it is so meane, as that it scant deserveth the name of an invention: for as the countryman by chance sometime findeth a great treasure, without any use of skill or cunning, so hath it happened herein."

He will "speake freely of the great use of this invention; I call it great, being greater than any of you expect to come from me . . . the use and effects of which, your selves shall sufficiently witness by your continual experiences."

He remarks that the world has become "a Paradise, abounding in some places with such things as the Earth cannot bring forth in other." This is due to "computation Astronomicall," which has made world navigation possible by assisting the pilot to determine the "elevation of the Equator and of the Pole, by meanes of the declination of the Sunne," and "to describe the true longtitudes, Latitudes, situations and distances of places." "But as the sweet is never without the sowre," these things cannot be done without great "travayle in such computations, namely in the busy multiplications and dimensions which proceed of the sixty progression of degrees, minutes, seconds, thirds &c. And the Surveyor or Land-meater knowth, what great benefite the world receyveth from his science . . . besides, he is not ignorant (especially whose business and imployment is great) of the troublesome multiplication of Roods, Feete and oftentimes of ynches, the one by the other, which not only molesteth, but often also (though he be very well experienced) causeth error, tending to the damage of both parties as also to the discredit of land-meater or surveyor, and so for the Money-masters, Marchants and each one in his business . . ."

Stevin says that his system "teacheth the easy performance of all reckonings, computations, and accounts, without broken numbers." Through it "wee gaine the time which is precious," and avoid "the paines, controversy, error, dammage, and other inconviniences commonly hapning therein." Nor need it be accepted without test, for unlike certain inventions that "at first seeme good, which when they come to be practiced, effect nothing of worth, as it often hapneth to the serchers of strong moving, which seeme good in small proofs and modells, when in great, or coming to the effect, they are

not worth a Button: whereto we answer, that herein is no such doubt: for experience dayley sheweth the same: namely, by the practize of divers expert Land-meaters of Holland, unto whom we have shewed it . . . who do use the same to their great contentment. . . . The like shall also heppen to each of yourselves using the same as they doe: meane while live in all felicity."

Stevin advocated the introduction of decimal coinages and weights and measures. The invention of positional notation in the canalized region of Babylon and its re-invention in the canalized Holland is notable.

Stevin's decimal system was not adopted quickly. Though it was inspired by commerce, merchants did not immediately see its advantages. It does not follow that because inventions and science have been created through the demands of commerce and industry, they will be immediately adopted by commerce and industry after they have appeared. One of the paradoxes of history is that science is a product of human demands, and yet is not necessarily used when it becomes available. Science has evolved from crafts and industry, and has created new industries, and yet science is still starved by industries and governments. This is not difficult to understand. Inventors and scientists are the extrapolators of the social perspective in which they live. A man such as Stevin satisfied great needs, of which his less penetrating contemporaries were unconscious, or to which they were selfishly indifferent. Society does not advance at the rate of its most gifted members, and yet it determines the general direction in which they go; nor are its most creative activities free from frustration by selfish classes within its own structure.

Stevin started as a merchant's clerk in Antwerp, and owing to his knowledge of mechanics he was appointed director of land and water construction in Holland. William the Silent made him Quartermaster General of the Dutch Army. He introduced commercial methods of bookkeeping into the manage-

ment of the Dutch finances. This was the first time that the bookkeeping of a state was conducted according to bourgeois conceptions.

Stevin was the technical organizer of William's successful resistance to Spanish domination. He was the leading military engineer of the day and superintended the construction of the Dutch fortifications. As a patriot he insisted on writing his works in his native language, because "our own Flemish language is the richest, the most ornate and the most perfect of all languages."

He constructed a land carriage propelled by sails, which carried twenty-eight people and outstripped galloping horses on the seashore.

He published a treatise on mechanics in 1586 in which he deduced the conditions of equilibrium from the behaviour of a continuous chain supported on a smooth triangular beam. It is known that such a ring will not slide round in perpetual motion, and yet the lengths of chain resting on the two supporting slopes may not be equal. Stevin deduced the tensions in networks of strings from the observation of the equilibrium of the chain, and implicitly used the parallelogram of forces. He deduced from pulleys the principle of virtual work.

His studies of hydraulics in connection with canalization led to equally valuable results. He demonstrated the hydrostatic paradox that the pressure on the bottom of a vessel of water does not depend on its shape but on its depth. He noted that one pound of water in a narrow tube could easily exert a pressure of one hundred thousand pounds on a broad piston, and discovered the principle of the hydraulic press. He proved by experiment the existence of upward pressures in liquids, and implicitly used the principle afterwards demonstrated by Pascal, that the pressure at any point in a liquid is the same in all directions. He found the total pressure on the side of a vessel by a method of limits which foreshadowed the integral calculus, and he investigated the equilibrium of floating bodies.

He showed that if a floating body was stable, its centre of gravity was in the same vertical line as that of the displaced liquid, and he applied his result to the design of ships.

Finally he was the first to publish a clear experimental refutation of Aristotle's theory of motion. In his work of 1586 he describes an experiment made in collaboration with a brother of the jurist Hugo Grotius. He writes (in F. S. Taylor's translation): "The experiment against Aristotle is this: let us take (as I have in company with the learned H. Jan Cornets de Groot, most diligent investigator of Nature's mysteries) two leaden balls, one ten times greater in weight than the other, which allow to fall together from a height of thirty feet upon a board or something from which a sound is clearly given out, and it shall appear that the lightest does not take ten times longer to fall than the heaviest, but that they fall so equally upon the boards that both noises appear as a single sensation of sound. The same, in fact, also occurs with two bodies of equal size but in tenfold ratio of weight."

Through such men as Stevin, the commerce and industry of the small country of Holland annexed Spanish trade and withstood the armies of the Spanish Empire.

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GALILEO PERFECTS THE METHOD OF PHYSICAL SCIENCE

The method of research in physical science which has proved so successful during the last three centuries first appears in its complete form in Galileo's *Dialogues Concerning Two New Sciences*. This treatise was published in 1638, when the author was seventy-four years old and had been collecting and developing his material for fifty years. The two new sciences that he claims to have invented were the theory of the strength of materials and structures and the theory of motion.

Galileo himself has stated in the first paragraph of his treatise the social activity from which the theory of the strength of materials and structures was derived. He introduces Salviati as saying:

"The constant activity which you Venetians display in your famous arsenal suggests to the studious mind a large field for investigation, especially that part of the work which involves mechanics; for in this department all types of instruments and machines are constantly being constructed by many artisans, among whom there must be some who, partly by inherited experience and partly by their own observations, have become highly expert and clever in explanation."

To which Sagredo answers:

"You are quite right. Indeed, I myself, being curious by nature, frequently visit this place for the mere pleasure of observing the work of those whom, on account of their superiority over other artisans, we call 'first-rank men.' Conference with

them has often helped me in the investigation of certain effects including not only those which are striking, but also those which are recondite and almost incredible."

The Venetian arsenal was at least four centuries old in Galileo's time. It had been described three centuries before by Dante. He writes in the twenty-first canto of *The Divine Comedy* of the mariners:

> In the Venetians' arsenal as boils
> Through wintry months tenacious pitch, to smear
> Their unsound vessels; for the inclement time
> Sea-faring men restrains, and in that while
> His bark one builds anew, another stops
> The ribs of his that hath made many a voyage,
> One hammers at the prow, one at the poop,
> This shapeth oars, that other cables twirls,
> The mizen one repairs, and mainsail rent;
> So, not by force of fire but art divine
> Boiled here a glutinous thick mass . . .

Galileo also noticed the activities and experiences of the shipwrights. He had learned from them that if a large ship was built in the same proportions as a seaworthy small ship it was liable to collapse on the stocks. Similar experiences were drawn from architecture.

A nail driven into a wall supported very much less than half the weight supported by a nail of twice the thickness.

He showed that these effects follow from the uniformity of the tensile strength of the material, combined with its size and shape. When a big ship was made out of the same material as a small one, the strength of the material in both cases was the same, though the sizes were different. If the two ships had similar shapes, they could only have the same strength if the strengths of the materials of construction were in a due proportion. He derived approximate formulae for the strength of rods, and explained why tubes containing the same amount of material were stronger. He deduced the design of a beam thick-

ening towards the middle so that the flexion at all points should be the same.

He applied his results to the whole of nature. He explained that the size of trees was limited by the strength of their wood, and the proportions of big trees are different from those of small trees. Human giants are impossible because beings of similar shape made of the same materials would collapse. Whales could grow to larger proportions than land animals because their weight is supported by the water, and not by limbs. He explained that bones are usually hollow because this form gives the maximum strength with lightness. He sketched a bone for a hypothetical giant animal, making the changes in proportion necessary for providing the requisite strength, and showed that it would be impracticably clumsy.

He measured the tensile strength of materials, and discussed its origin. This led him to consider the theory that tensile strength is due to the vacuum. According to Aristotelian ideas, nature abhors a vacuum, so the constituent particles of a solid body might cling together in their anxiety to avoid a vacuum. Galileo measured the force with which very smooth plates in sliding contact stick together, and regarded it as due to the resistance to the vacuum.

He conceived a more satisfactory experiment to measure the resistance to the vacuum. He believed that water is without cohesion and is held together entirely by the resistance to a vacuum. The tensile strength of water is therefore a direct measure of the resistance to the vacuum. He made a smooth cylinder with a well-fitting plug. The plug contained a valve through which the cylinder could be completely filled with water. The cylinder was inverted and securely suspended, and weights were attached to the plug. He had constructed a column of water which could be submitted to tension by weights like a brass wire. He had shown that all vertical rods suspended from the end break under their own weight when they exceed a certain length, depending on the tensile strength of their ma-

terial. From this he advanced to the conception of a limiting length of a rod of water suspended from the top of his cylinder.

He deduced from common experience with pumps what this length might be.

He describes how he had heard of a pump that "worked perfectly so long as the water in the cistern stood above a certain level; but below this level the pump failed to work. When I first noticed this phenomenon, I thought the machine was out of order; but the workman whom I called in to repair it told me the defect was not in the pump but in the water, which had fallen too low to be raised through such a height; and he added that it was not possible, either by a pump or by any other machine working on the principle of attraction, to lift water a hair's breadth above eighteen cubits." That is, above twenty-four feet.

He concludes: "And really is not that thing which is attracted in the pump a column of water, attached at the upper end and stretched more and more until finally a point is reached where it breaks, like a rope, on account of its excessive weight?"

As he believed water was without cohesion, he deduced that the resistance to the vacuum was equivalent to the pressure of a column of water twenty-four feet high.

Brass and other materials could not be held together exclusively by resistance to a vacuum, because the limiting lengths at which they broke under their own weight were vastly greater than the equivalent of twenty-four feet of water. He supposed that their extra strength was due to a viscous binding substance which held the constituent particles together with a force far greater than the resistance to the vacuum.

Galileo demonstrated that the resistance to the vacuum was limited, and equivalent to the pressure of a column of water twenty-four feet high, but he did not identify this resistance with the pressure of the atmosphere. Galileo's figure of twenty-four feet for the resistance of the vacuum is exactly the same as

that given by Agricola in 1556, eight years before Galileo was born, for the maximum lift of a suction pump.

Galileo expounds his new science of motion in three sections, dealing with uniform motion, naturally accelerated motion, and the application of the theory of these two types of motion to the analysis of the flight of projectiles. His general theory is expressed in thirty-eight propositions, and various problems, lemmas and scholia cast in a rigid Euclidean form. This extended, systematic theory of motion was new, and also included many ingenious solutions of difficult theorems. But Galileo's philosophical comments were even more striking.

He says: "It has been observed that missiles and projectiles describe a curved path of some sort; however, no one has pointed out the fact that this path is a parabola. But this and other facts, not few in number or less worth knowing, I have succeeded in proving, and what I consider more important, there have been opened up to this vast and most excellent science, of which my work is merely the beginning, ways and means by which other minds more acute than mine will explore its remote corners."

The root of his achievement lay in his successful analysis of the motion of falling bodies. He explained his mode of approach. He would ignore discussions of the cause of motion and restrict himself to an investigation of how it occurred.

He says of proposed causes of motion that "all these fantasies, and others too, ought to be examined; but it is not really worth while. At present it is the purpose of our Author merely to investigate and to demonstrate some of the properties of accelerated motion." Galileo starts by recalling his observations and technical processes. He refers to the phenomena of pile-driving, which provides an example of a body falling freely.

"Tell me, gentlemen," he says, "is it not true that if a block be allowed to fall upon a statue from a height of four cubits and drives it into the earth, say four finger breadths, that falling from a height of two cubits it will drive the stake a much less

distance. . . ." The decrease in effect must be due to decrease in speed of impact, and this must be related to the shorter distance of fall. What is this speed? After observing the common facts of falling bodies, a definition, or theory, of the law of increase of speed with fall must be propounded. He says:

"First of all it seems desirable to find and explain a definition best fitting natural phenomena. For anyone may invent an arbitrary type of motion and discuss its properties . . . but we have decided to consider the phenomena of bodies falling with an acceleration such as actually occurs in nature and to make this definition of accelerated motion exhibit the essential features of observed accelerated motion."

He believes that, after repeated efforts, he has succeeded in doing this. He finds the proof from the consideration "that experimental results are seen to agree with and exactly correspond with those properties which have been, one after another, demonstrated by us." He states the intellectual principle which guided his invention of theories for experimental test. He says: "Finally, in the investigation of naturally accelerated motion we were led, by hand as it were, in following the habit and custom of nature herself, in all her various other processes, to employ only those means which are most common, simple and easy."

He adopted the principle of simplicity as the guide to the formulation of theories for experimental test. As already mentioned, Dirac has recently stated that he considers this the characteristic intellectual method of the Newtonian period in physical science, in contrast with the principle of beauty, which was used to find the theories of relativity and quanta, needed to describe experimental observations of recent physics.

Galileo continues: "When, therefore, I observe a stone initially at rest falling from an elevated position and continually acquiring new increments of speed, why should I not believe that such increases take place in a manner which is exceedingly simple and rather obvious to everybody?"

The first simple hypothesis that occurred to him was that the speed should be proportional to the distance of fall. He examined the logical implications of this hypothesis before he tested it experimentally, and fallaciously concluded that if it were true, falling would be instantaneous, which is in fact contradictory both to the hypothesis and to observation. Having rejected this hypothesis by fallacious logic, he considered the hypothesis that the speed is proportional to the time of fall. He examined its logical implications and could find none in contradiction to experience, so he proceeded to experimental tests. As he had no satisfactory apparatus for demonstrating directly that the speed is proportional to the time of fall, he deduced that the hypothesis implied that the distance fallen was proportional to the square of the time of fall. Even that was too difficult to test directly, owing to the speed of freely falling bodies, so he devised a method of retarding their rate of fall. He did this by rolling them down an inclined plane. This was made of "a piece of wooden moulding or scantling about 12 cubits long." He measured the time for a "hard, smooth, and very round bronze ball" to roll down the plane, and then measured the times for one-half, one-third, one-quarter and other fractions of the length. "In such experiments, repeated a full hundred times, we always found that the spaces traversed were to each other as the squares of the times, and this was true for all inclinations of the plane."

The intervals of time were measured by an accurate water-clock, which would measure to within one-tenth of a pulse-beat.

The chief feature in this experiment was the systematic test, not by one but by hundreds of experiments for many varieties of experimental arrangement.

Galileo deduced the law for free fall from the law for inclined fall with the aid of the assumption that the speed at the end of any fall, vertical or inclined, would be the same if the height of the fall were the same.

He proved by logic and experiment that this assumption was true. If it were untrue, then a body could raise itself by its own weight. We must believe that if the motion of a body is suddenly reversed, the body will return to its original position.

Now what would happen if two inclines of equal height but different slope were placed together, so that a body could be rolled down them like a switch-back? If the body were rolled down the slope which gave it the higher speed, it would be shunted up the other slope with a greater speed than it could have gained by falling down that slope. Hence it would rise higher than its original height.

In addition to this logical proof, Galileo provided an experimental proof. He fastened the string of a pendulum to a nail in a wall. He displaced the bob so that it could swing freely along the face of the wall, and noted that it always rose to the same height at each end of the swing. He then fixed a pin in the wall, vertically below the supporting nail, so that the string was caught halfway through the swing. He noted that even then the bob rose to the same height at the opposite end of its swing. The same result was obtained when the pin was placed at various points on the vertical line beneath the nail so long as it was above the level to which the bob was swinging. Galileo explained that the various arcs traversed by the bob were equivalent to combinations of frictionless inclined planes, so the experiment proved that all combinations of such planes restored the fallen body exactly to the level from which it had fallen, and neither above nor below. Hence the speed at the end of a fall down any inclined plane depends only on the height.

Galileo deduced the law of uniform motion as the limiting case of accelerated motion. Suppose a body ran down an inclined plane and was shunted up a rising plane. Its deceleration up the rising plane would be the less the smaller the slope, and if the slope were zero, and the plane horizontal, the deceleration would be zero. Thus the body would continue forever at uniform speed.

Galileo then states the two laws of motion in his analysis of the trajectory of a projectile, and compounds two velocities. He says:

"Imagine any particle projected along a horizontal plane without friction; then we know, from what has been more fully explained in the preceding pages, that this particle will move along this same plane with a motion which is uniform and perpetual, provided the plane has no limits. But if the plane is limited and elevated, then the moving particle, which we imagine to be a heavy one, will on passing over the edge of the plane acquire, in addition to its previous uniform and perpetual motion, a downward propensity due to its own weight; so that the resulting motion, which I call projection, is compounded of one which is uniform and horizontal and of another which is vertical and naturally accelerated. We now proceed to demonstrate some of its properties . . ."

He proves that the path of the particle must be parabolic, and deduces 45° as the elevation for the maximum range, and says that "from accounts given by gunners, I was already aware of the fact that in the use of cannon and mortars, the maximum range, that is the one in which the shot goes farthest, is obtained when the elevation is 45°."

He then illustrates how the establishment of a correct theory enables the scientist to discover facts previously unknown. He deduced from the properties of the parabolic path "what has perhaps never been observed in experience, namely, that of other shots those which exceed or fall short of 45° by equal amounts have equal ranges."

Galileo had given a complete exposition of the nature and manipulation of the method of scientific research, and he had evolved it primarily from the analysis of facts provided by shipwrights, builders, gunners, and other technicians, and from the work of predecessors who had derived their knowledge from similar sources.

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GALILEO OPENS THE WINDOW OF THE UNIVERSE

Galileo achieved far more fame during his life by his contributions to astronomy than by his perfection of scientific method. He was born in Pisa, and was the son of a musician whose family had been prominent in Florence for centuries, until the Florentine Republic was overthrown. His father was a musician who considered himself a nobleman, but was impoverished. He earned little from music, so he desired his son to enter the wool trade. As Galileo early showed intellectual ability, his prospective career was changed to medicine. He was given a thorough literary education in a Benedictine monastery and sent to study at the University of Pisa. He transferred his interest to physical science, but his first discovery was due to his combination of medical and physical interests. He noted the constancy of the time of oscillation of the pendulum by comparing it with his pulse, and applied it to the measurement of the pulse. At the end of his life he prepared a design for a pendulum clock.

He investigated the centre of gravity of solid bodies on the suggestion of the Marquis Guidubaldo, who was an enthusiastic mathematician. By Guidubaldo's aid, and his own strenuous soliciting, he was appointed professor of mathematics at Pisa with an annual salary of £13. He was not comfortable at Pisa and, in 1592, secured the chair of mathematics at Padua, again through Guidubaldo, who exerted his influence with the Venetian senate, which controlled the university. His annual salary was fixed at £32. Lectures on artillery and fortifications were

an important part of his professional duties. He wrote a treatise on fortification, and invented the proportional compasses, or sector, which were of great value to military engineers. The Venetian Senate made much use of Galileo's knowledge of engineering for its defensive and offensive armaments. Owing to this, he received an invitation in 1604 from the Duke of Mantua to become his military engineer.

Galileo made many of his investigations in mechanics while he was at Padua. He organized the manufacture of the instruments he had invented, and lectured on their use.

Audiences of two thousand persons attended his lectures, and his fame spread. Kepler probably sent him a copy of his *Prodromus Dissertationum Cosmographicarum*, as a letter of thanks from Galileo exists. This was written in 1597, and in it Galileo says: "Many years ago I became a convert to the opinions of Copernicus, and by that theory have succeeded in fully explaining many phenomena, which on the contrary hypothesis are altogether inexplicable. I have drawn up many arguments and confutations of the opposite opinions, which, however, I have not hitherto dared to publish, fearful of meeting the same fate as our master Copernicus, who, although he has earned for himself immortal fame amongst a few, yet amongst the greater number appears as only worthy of hooting and derision; so great is the number of fools. I should indeed dare to bring forward my speculations if there were many like you; but since there are not, I shrink from a subject of this description." Kepler replied that he should continue his speculations and publish in Germany his defence of the Copernican theory. Galileo did not follow this advice, nor in later years did he show any appreciation of Kepler's discoveries of the laws of planetary motion.

Galileo heard a rumour in 1608 that some Dutchmen had invented an instrument with two lenses which magnified distant objects.

The printing of books, which was a fairly new industry,

had grown with exceptional rapidity in Holland, owing to the greater freedom of opinion. This was accompanied by an increase in the number of readers, and in the demand for spectacles. Dutch opticians created a flourishing lens industry to meet this need. Casual experiments with combinations of lenses were made, and two mechanics at Middelburg, Jansen and Lippershay, discovered at some time between 1581 and 1608 that lenses could be combined to form microscopes and telescopes. Lippershay received a secret order from the Dutch government on October 2, 1608, for a telescope.

Galileo meditated on the rumour. He soon worked out the optical principles of the instruments, and presently made a telescope that would magnify more than ten diameters.

He was commanded to show it to the Doge of Venice. He has left a description of one of his demonstrations to the nobility. He said:

"Many gentlemen and senators, even the oldest, have ascended at various times the highest bell-towers in Venice, to spy out ships at sea making sail for the mouth of the harbour, and have seen them clearly, though without my telescope they would have been invisible for more than two hours. . . . Perceiving of what great utility such an instrument would prove in naval and military operations, and seeing that his Serenity greatly desired to possess it, I resolved to go to the palace and present it to the Doge as a free gift."

Galileo did this, and his professorship at Padua, which he had held for seventeen years, was made a life appointment and his annual salary was raised to 1,000 florins.

Bernal has quoted Galileo's letter to the Doge in which he remarked that the new instrument was of inestimable benefit to every maritime and terrestrial affair. "One is able to discover enemy sails and fleets at a distance greater than customary, so that we can discover him [the enemy] two hours or more before he discovers us and, by distinguishing the number and quality of the vessels, judge of his force whether to

set out to chase him, or to fight, or to run away. . . . Also on land can one look into the squares, buildings, and defences of the enemy."

He directed his instrument to the heavens, and was astounded by his observations. He had found that he had, as it were, opened a window into the outer universe. Without the telescope, the heavens had appeared like a surface ornamented by stars. With it, the vast depth of the universe was revealed. The three-dimensional outer universe had been a mathematical deduction, now the third dimension was revealed in observation.

"Being infinitely amazed thereat," he wrote to Vinta, the secretary of the Grand Duke of Tuscany, "so do I give infinite thanks to God, who has been pleased to make me the first observer of marvellous things, unrevealed to bygone ages." He had discovered the ridges on the moon, and estimated their height from the length of their shadows. He had found that the Milky Way consisted of myriads of stars, and that the number of fixed stars was at least ten times as many as those visible to the naked eye. He presently saw the discs of the planets for the first time, and noted the phases of Venus. He independently discovered sun spots and the rotation of the sun.

"But the greatest marvel of all," he said, "is the discovery I have made of four new planets." These were satellites of Jupiter.

Galileo had been seeking before these events to secure an invitation to the Medicean court at Florence. In spite of his fame and activity in Padua, he wished to return to Tuscany. He accepted the permanent appointment to the Paduan chair only because the Florentine negotiations were stationary, and, as he described it, "Fortune's wings are swift, but those of Hope are drooping."

His pupil Prince Cosimo de' Medici had recently inherited the dukedom, so Galileo started his discreet soundings. Before he had constructed his telescope, he wrote confidentially to

personages at Florence that "having now laboured for twenty years, and these the best years of my life, in dealing out, so to speak, by retail, to all who chose to ask, that small portion of talent, which, through God and my own labour, I have gained in my profession, my desire would be, to possess such rest and leisure as to be able to conclude three great works which I have in hand, and to publish them before I die."

He did not believe that he could obtain more leisure than he possessed at Padua if he had to continue to lecture to support his family.

"It is impossible to obtain from a Republic, however splendid and generous, a stipend without duties attached to it; for to have anything from the public one must work for the public, and as long as I am capable of lecturing and writing, the Republic cannot exempt me from this duty while I enjoy the emolument. In short, I have no hope of enjoying such ease and leisure as are necessary to me, except in the service of an absolute prince."

Soon after writing this letter, he made the astronomical discoveries, and decided to name the satellites of Jupiter the Medicean stars. Keen interest in him was now aroused in Florence, and he was offered an appointment without routine duties at an annual salary of about £200. He wrote that he proposed to earn his emolument by writing. The profusion of his ideas did him harm and many of them could be of use only to princes who "alone make war" and "erect fortresses." The works he wished to finish were "two books on the system of the universe; an immense work full of philosophy, astronomy, and geometry, three books on locomotion, a science entirely new, no one, either ancient or modern, having discovered any of the marvellous accidents which I demonstrate in natural and violent motions."

He would write three volumes on statics which would contain four times as much as was known to his predecessors.

"I have also various treatises on natural subjects, on sound

and speech, on sight and colours, on the tide, on the composition of continuous quantity, on the motions of animals, and others; besides, I have also an idea of writing some books on the military art, giving not only a model of a soldier, but teaching with very exact rules all which it is his duty to know that depends on mathematics, as for instance, the knowledge of encampment, drawing up battalions, fortifications, assaults, planning, surveying, the knowledge of artillery, the use of various instruments, etc."

He wished to prepare a new edition of his tract on the sector, and mentioned that several thousands of the instrument had been sold. He also wished to work out the periods of Jupiter's satellites. Finally, he wished to be named philosopher, besides mathematician, to the Duke because he professed "to have studied a greater number of years in philosophy than months in pure mathematics."

Galileo left the Republic of Venice for the despotism of Florence in 1610. He became the intellectual ornament of the Medicean court. He visited Rome in 1611 under the auspices of the Grand Duke, and exhibited his telescopes to the ecclesiastical dignitaries, amid great applause.

The discovery of Jupiter's moons provided strong evidence for the Copernican theory. If Jupiter, which was a great luminary, was the centre of a miniature planetary system, then it seemed by analogy that the great luminary of the sun should also be the centre of its planetary system.

The arguments for and against the Copernican system were discussed in high excitement at many places, including the Grand Ducal court. Scientists were invited to the Grand Ducal table to assist in the discussions. Castelli was one of these. He supported the Copernican theory enthusiastically. The Grand Duchess was keenly interested, but feared the theory was heretical. Castelli wrote to Galileo describing his discussions, and Galileo, happy at the august interest, replied with incautious enthusiasm in a letter written in December, 1613. He

wrote that the Grand Duchess had spoken well when she said that the Holy Scriptures could not err, and "that the decrees therein contained are absolutely inviolable." But he would have added that "though Scripture cannot err, its expounders and interpreters are liable to err in many ways." The most grave errors arise from literal interpretation. If this is accepted, God would have limbs and passions, forgetfulness and lack of foresight. Many propositions in the Scriptures are accommodated to the capacity of the vulgar. But "for those few who merit to be separated from the plebeian crowd, it is necessary for wise expositors to produce the true meaning." This is especially necessary in the interpretation of matters involving mathematics. Holy Scripture and nature are both emanations from the Divine word. The first has to be accommodated to the vulgar. "But Nature being on the contrary inexorable and immutable, and caring not one jot whether her secret reasons and modes of operation be above or below the capacity of men's understanding, it appears that, as she never transgresses her own laws, those natural effects which the experience of the senses places before our eyes, or which we infer from adequate demonstration, are in no wise to be revoked because of certain passages of Scripture."

When an apparent discordance between Scripture and observation occurs, it is the business of wise expounders to investigate whether the conventional interpretation is correct. He believes that it would be "prudent if men were forbidden to employ passages of Scripture for the purpose of sustaining what our senses or demonstrated proof may manifest to the contrary. Who can set bounds to the mind of man? Who dares assert that he already knows all that in this universe is knowable?"

He believes that the "articles concerning salvation and the stability of the faith" are the core of religion, and that no unnecessary assertions about the world should be added to them, even by persons who, though they may be divinely inspired, yet

we see clearly "are destitute of the intelligence necessary, not merely to disprove, but to understand those demonstrations by which scientific conclusions are confirmed."

The Dominicans secured a copy of this letter and forwarded it to the Inquisition. Galileo travelled to Rome, with a personal letter of introduction from the Grand Duke to one of the cardinals, to defend his doctrine. In spite of his powerful arguments and influence, he was not exculpated. He was admonished, and instructed not to promulgate the Copernican theory by writing or in any other way. Copernicus' treatise and all other works supporting his theory were banned.

Galileo returned to Florence and continued his preparation of the *Dialogue on the Two Systems of the World.*

In 1618 three notable comets appeared. These inspired a tract on comets, written by a pupil under Galileo's supervision. It contained strictures on the views of the Jesuit Grassi and increased the order's enmity towards Galileo.

Cardinal Barberini, who had been one of Galileo's most sympathetic supporters among the prelates, was elected Pope in 1623. Galileo and his friends hoped he would remove the prohibition against the Copernican theory. He visited the new Pope in 1624 and was very well received.

He continued writing his *Dialogue on the Two Systems*, and presently, in 1630, these were finished. He had now to secure a licence from the Pope for their publication. He travelled to Rome in May, and was informed that the Pope would give the permission if it were plainly stated in the book that the Copernican theory was merely a hypothesis, and if the book were concluded with an argument against the theory composed by the Pope himself. Galileo agreed, and the manuscript was returned to him with the licence. The work was published in Florence in January, 1632.

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SCIENCE AND FREEDOM

The Inquisition suddenly ordered, in August, 1632, the sequestration of all copies of the *Dialogue on the Two Systems of the World.*

Galileo was astonished, and complained to the Grand Duke of Tuscany, who instructed Niccolini, his ambassador in Rome, to express his surprise, and register a protest. The Pope snubbed Niccolini, and desired him to inform the Grand Duke that he expected help and not hindrance from him in matters concerning theology.

Galileo was summoned to the office of the Inquisition for examination. After delays, he arrived in Rome in 1633. His affairs were conducted with great skill by Niccolini, who was one of the few among Galileo's friends who understood the Roman political currents. The ambassador was supporting the reputation of a great countryman, and was unwilling to see him degraded.

Galileo was frail, and sixty-nine years old, and knew he was intellectually in the right. He had a lively temperament, and had difficulty in restraining it. Niccolini advised him to be completely submissive and recommended him to agree even to deny the Earth's motion. He reported that "this advice of mine has afflicted him extremely: so much so, that ever since yesterday he has been in such a state of prostration that I have my fears for his life."

The Inquisition felt that there were already too many independent thinkers in Florence. Besides this political opposition to Florence, the Pope's personal feelings had been ruffled. He had been informed that his argument had been put into

the mouth of Simplicio, the Aristotelian butt in the *Dialogue*. He was also convinced that Galileo's doctrine was bad and that Galileo certainly believed his own doctrine.

Niccolini continued his entreaties, but the Pope told him he must do what was necessary for the furtherance of the Christian faith.

Galileo was treated by the Inquisition with a consideration unexampled in its history. He was allowed at first to stay with Niccolini, instead of being cast, like all former prisoners, including princes, prelates and noblemen, into the dungeons.

Even when he was removed to the Office for questioning, he was not put in the dungeons, but was accommodated in the officers' quarters. But the separation from his friends upset him, and he was very miserable.

The Commission of Cardinals that conducted the examinations was apparently not unsympathetic, and interceded with the Pope for his release from the Office. The Pope consented to a conditional release, and he was allowed to return to Niccolini's house.

When Galileo was examined for the third time, he discovered that he had misunderstood the admonishment of 1616. He had not realized that it limited his liberty to write, and he had transgressed this limitation.

He had believed he would be liberated shortly, and now he found himself "vehemently suspected of heresy," and condemned. He was menaced with torture, and whether or not it was to be applied, he expected it, for he replied:

"I am in your hands; do as you please with me." The minute of the examination states: "And as nothing more could be got from him he was remanded."

He was commanded to abjure his heresies, which he did. He was sentenced to imprisonment during the pleasure of the Inquisition, and was detained at Siena, and then in his own house at Arcetri.

None of the documents relating to the trial of Galileo is

officially ratified by the Pope. The decree of 1616 and the sentence of 1633 are merely the fallible judgment of an assembly of cardinals.

Galileo's friends burned as many of his private papers as they could find after his condemnation. He was continually watched by spies. When he was first summoned to Rome he became despondent and wrote that he detested the remembrance of all the time he had consumed in study. After the trial, he said that he had lost interest in research. "The pleasure which I have taken hitherto in making observation on new phenomena is almost entirely gone."

He wrote in 1636 to Peiresc, the French ambassador at Rome, who had attempted to assist him: "I have said, my lord, that I hope for no alleviation; and this is because I have committed no crime. If I had erred, I might hope to obtain grace and pardon; for the transgressions of the subject are the means by which the prince finds occasion for the exercise of mercy and indulgence. Wherefore, when a man is wrongly condemned to punishment, it becomes necessary for his judges to use the greater severity, in order to cover their own misapplication of the law."

According to his life-long habit, he continued to work, though without enthusiasm. His greatest achievement, the *Dialogues on Two New Sciences*, was finished in 1636 and published in 1638.

He discovered the variations of the moon in 1637, just before he went blind. He wrote of this: "I have observed a most marvellous appearance on the surface of the Moon. Though she has been looked at such millions of times by such millions of men, I do not find that any have observed the slightest alteration in her surface, but that exactly the same side has always been supposed to be represented to our eyes. Now I find that such is not the case, but on the contrary that she changes her aspect, as one who, having his full face turned towards us, should move it sideways, first to the right and

then to the left, or should raise and then lower it, and lastly incline it, first to the right and then to the left."

He noted that these variations were daily, monthly and yearly.

Galileo's condition at that time was noticed by Milton, who visited him about 1638, and referred to the occasion in his pamphlet *Areopagitica*, on the freedom of the press. He wrote:

"I could recount what I have seen and heard in other countries, where this kind of inquisition tyrannizes, where I have sat among their learned men, for that honour I had, and bin counted happy to be born in such a place of Philosophic Freedom, as they suppos'd England was, while themselves did nothing but bemoan the servil condition into which Lerning amongst them was brought; that this it was which had dampt the glory of Italian wits; that nothing had been there writt'n now these many years but flattery and fustian. There it was that I found and visited the famous Galileo, grown old, a prisner to the Inquisition, for thinking in Astronomy otherwise than the Franciscan and Dominican Licencers thought."

Galileo still bargained with the powers for the sale of his method of determining longitudes at sea from Jupiter's satellites.

Bernal has drawn attention to an interesting feature of this bargaining. In 1616, Galileo had offered it to the King of Spain at the price of a grandeeship and a large sum of money, with the remark that he had "neither ports nor islands, nor provinces nor realms, nor even ships to go visiting there. It is the enterprise for a great monarch. . . . No other crown in the world today is more fit for that than Spain." His offer was not accepted. Then, in 1637, he offered it to the States-General of Holland. He said: "I have chosen to present it to these illustrious gentlemen, rather than to some absolute prince, because when the prince alone be not capable of understanding this machine, as almost always happens, having to rely on the advice of others, very often not very intelligent . . ." the mat-

ter is not understood and the offer rejected. "But in a republic, when the deliberations depend on the opinion of many, a small number and even a single one of the powerful rulers, moderately knowledgeable about the proposed matter, may give the others courage to lend their consent." But the States-General also failed to accept his offer. The method was not, in fact, as practicable as Galileo believed.

Galileo became head of his family in 1591. His brother and his own son were wastrels, and he had to pay his sister's dowry. He was never married, but had three children by a Venetian woman of lower social class. He secured a special dispensation from the Church to put his two daughters into a nunnery before they were sixteen years of age. He persuaded the Grand Duke of Tuscany to legitimize his son.

Though Galileo had a strong sense of family duty, he appeared to have no sense of political duty. He did not foresee that his departure from the relative freedom of the Republic of Venice for the deceptive attractions of his own country, and payment without duties under an absolute prince, would ruin his happiness and self-respect.

The Papacy feared to attack Venice because the Venetians astutely flirted with the Protestant powers, and if menaced might have introduced the Reformation into Italy.

If Galileo had had political understanding, he would have remained there, or at least have returned there in 1616, after the first admonishment by the Inquisition. He did not perceive that the Medicean Grand Dukes could not protect him in the last resort, because they were politically bound with the Papacy. Nor did he understand that his conflict with the Inquisition was a social and political and not an intellectual matter. The disorder of the Papacy, which had culminated in the pontificate of the Borgia, had led to reorganization. The Commission of Cardinals in 1537 had reported on its condition, and the order of the Jesuits was in process of formation. The Inquisition was renewed in 1542, and in 1559 the Index Expurga-

torious was begun. These were the weapons of the Counter-Reformation.

Giordano Bruno was burned in Rome in 1600, for supporting the Copernican theory and other heresies, when Galileo had already achieved fame. Galileo had grown up in Tuscany under Francesco de' Medici, who inherited the dukedom in 1574. One hundred and sixty-eight murders occurred in Florence during the first eighteen months of his reign.

Italian society was declining through the transfer of power to the Atlantic countries. Its governing class, which had risen to power as merchants in the Middle Ages, had declined into a corrupt leisured class whose economic roots were decaying. It assisted the Spaniards in the creation of the Counter-Reformation and the renewed Inquisition as an effort to preserve its political power by force. The Spaniards did not need freedom, because they could obtain power by importing gold. Their north European opponents could obtain gold only by labour and invention. They were therefore in favour of the freedom conducive to industry and invention.

Galileo, who had grown up in a decaying society, did not understand that an independent intellectual attitude, which had been appropriate to a rising commercial class struggling for power against feudalism two centuries earlier, was no longer serviceable to the leisured class into which the successors of the earlier Italian merchants had been transformed. His attitude was appropriate only to merchants and individualists of northern Europe, who were the new aspirants for power. He did not see this. He did not understand that service under the Medicean prince was bondage.

Milton has described such a situation in his own moral terminology:

> But what more oft, in nations grown corrupt,
> And by their vices brought to servitude,
> Than to love bondage more than liberty—
> Bondage with ease, than strenuous liberty?

Galileo believed that science could be separated entirely from religion, and also from politics and commerce. He seemed to believe that its economic value, of which he was keenly aware, was accidental.

Galileo's views have been typical for scientists during the last three centuries, not only on scientific method, but also on the relations between science, religion and politics.

The position in which Galileo's views placed him has been described. Today, science as a whole, which still has his views, is finding itself in a similar position. The majority of its representatives believe that there is no necessary connection between science, religion and politics, and are trusting statesmen who sympathize with those who have once more revived the Inquisition for the preservation of declining governing class. They hope that those who have revived inquisitory methods for this purpose may ultimately be persuaded to ignore scientists and let them continue research in quiet and humble corners. They still support those who have preferred to go from London to Munich, instead of Washington and Moscow, as Galileo went to Florence instead of Amsterdam or London.

Those who have revived the Inquisition, like the Pope in Galileo's time, have a better understanding of politics, and realize that in crises the possession of power is more important than the cultivation of intellectual freedom.

The progressive class in western Europe in Galileo's time also understood very well that force must be used to preserve and extend its power. The Elizabethans fought like bandits, and Milton's friends also knew how to use force in the service of progress.

The danger and value of an Inquisition depend on whether it is used in behalf of a reactionary or a progressive governing class.

Cromwell's dictatorship limited the power of the old landed aristocracy, with its hankering for absolute monarchy and papism. He restricted freedom to free a new governing class.

Because this class was rising, it needed freedom and free thought, and when it secured power, it raised them to a degree not hitherto seen in the world. Freedom is now contracting with the decline of this class, and will expand again only after the power of its progressive successor has been established. The distinction between the use of force for the preservation of a declining class and for a rising class is of the utmost importance.

The failure to make the distinction exacerbates those who use force in the interests of progress. The greatest service that can be rendered to science in a period of crisis is to assist the struggle of the progressive class for power, so that this can be completed with as little trouble, and as quickly as possible. The hindering of the struggle of the progressive class makes it use inquisitory methods, and these may extend to a degree which draws protests like Milton's from its own supporters.

Milton's protest was correct, but the determination of the Cromwellians to win was more correct, even if they had to use inquisitory methods.

Freedom in itself has little meaning. It exists in the main only in so far as it is in the interest of some powerful social class. As Pirenne has remarked, Liberty is the device under which the commercial and industrial classes have fought for power. Freedom is advantageous to a rising class because facts are on its side, so that knowledge of them strengthens its cause. During progressive periods, it is convenient to detach the conception of freedom from the prevailing social conditions, and advocate its cultivation as an independent good. But this abbreviation of definition is permissible only when conditions are improving. The advocacy of the extension of freedom after the improvement has ended may be disastrous. Freedom was extended as good in itself in the German Republic while the social system was decaying. It temporarily assisted the growth of science, but at the same time provided the freedom

under which the protagonists of a decaying system could seize political power.

On the whole, freedom in the German Republic did more harm than good, owing to the social conditions of the period. Freedom in Ionia after emancipation from Babylonian and Egyptian theological domination, and freedom in the Atlantic countries after the limitation of the power of the landowners, was beneficial. Freedom and inquisition are social techniques of the same sort, but contrary direction. Sometimes one, and sometimes the other, and sometimes a combination of both, as under Cromwell, is justified. Freedom is beneficial to science when it provides opportunity to a rising class. Inquisition is beneficial to science when it protects a rising class. Freedom is inimical to science when it assists reactionary elements to gain power, and inquisition is inimical to science when it preserves the power of a declining class. The definition of a progressive class depends on political understanding and judgment. If the scientist wishes to enjoy freedom, he must be able to choose the progressive side. For this reason the scientist must study politics.

Galileo's career is a classical demonstration of what happens when a scientist ignores politics, for his conflict with the Church was in essence a political affair. He trusts to his personal ability in intellectual persuasion and to the political protection of reactionary powers, instead of seeking the protection of progressive powers, who will fight for him as well as argue, if necessary.

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FREEDOM IN THE INTEREST OF SKILL

The Spaniards believed that the gold of America would enable them to conquer the world. They already ruled Italy, Austria and the Netherlands, besides their own country, and the New World belonged to them.

The outlook for England, with her small population of six million and her backward development, was bad. Elizabeth, Cecil, and their colleagues planned to improve it. British industry and commerce could not supply the materials for the new warfare.

Saltpetre, sulphur and metals came from Catholic ports under Spanish influence, and were not sold freely to Protestant customers.

Mining in England was undeveloped, and iron and copper could not be easily bought abroad. Alum, which was of importance to the textile trade, came from Ischia, which belonged to the Pope.

The plan of development adopted by Elizabeth and Cecil had features which foreshadowed the plans of the government of the Soviet Union in recent times. They founded industries to provide munitions, including metal mining, brass-founding, and wire-drawing. They engaged the Augsburg capitalists as technical advisers to supervise those innovations.

As Cunningham writes: "Most important of all was the skill of German engineers; their methods of pumping water were introduced, and rendered mining possible where it had never been practiced before."

Copper mines were started at Keswick, and lead mines were

operated at Colbeck in 1564 by German miners. But no capital for these developments was borrowed from the Augsburg capitalists. It was subscribed within the country.

Agriculture was encouraged for military reasons, so that the country could supply strong, well-nourished soldiers. The fisheries were encouraged by compelling the population to eat fish on three days in the week, so that large numbers of skilled seamen would be available to man ships of war.

Capitalists were encouraged by the grant of monopolies to found glass, paper, starch and soap industries.

While Cecil refused to allow the import of foreign capital, he encouraged the import of skilled refugees.

Freedom was encouraged, not so much as an abstract good but as a means of increasing the national capital of industrial skill. By it, large numbers of skilled workers who had been persecuted in the Spanish Netherlands, Greece, Italy and Spain were attracted to England. In fact, the England of Elizabeth, with a population of six million, absorbed more refugees than contemporary England, with a population of forty-five million. The English people disliked these refugees, but were compelled by Cecil to absorb them. Their presence was advantageous to the governing class.

As a result of this policy, the English people and industry at the end of Elizabeth's reign were relatively prosperous, and the crown was relatively poor; whereas in Spain the crown was rich and the people and industry poor. Unlike Spain, England was able to supply her colonies with food and cloth without disorganizing her economy, and she had enough sailors, soldiers and munitions to resist aggression.

Holland increased her technical development still further, and for a century led Europe. The skill of her artisans gave her flexibility in adopting profitable new processes.

While the English crown developed industry by the encouragement of private capitalists, the French crown directly created new industries. The English policy strengthened the

middle classes and encouraged their initiative, but the French policy created uniformity of organization and opinion, which gave corporative strength, but hindered private initiative, and led to the absolute state of Louis XIV.

The economies of each country were unified, and completed the coalescence of their peoples and cities into nations.

History became the economic and political affairs of nations, and the state became supreme in politics when capitalism became supreme in wholesale trade.

The economic change transformed the bourgeoisie's outlook. As Pirenne remarks, the bourgeois of the Middle Ages was privileged by law, and the city was the centre of his life, but the modern bourgeois is privileged by virtue of his economic situation, and the city is merely his business centre and residence, while his interests are spread through the world.

This is the chief cause of the unsatisfactory nature of modern urban life.

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TO THE EFFECTING OF ALL THINGS POSSIBLE

The rapid increase in wealth and possibilities brought by the expansion of commerce and the discovery of the New World inspired optimism. Those classes that benefited most from the developments were the most optimistic. Their hopes were expressed by many writers. George Best, who was Martin Frobisher's lieutenant on two of his voyages, published *A True Discourse of the Late Voyages of Discoverie* in 1578, in which he praised the inventions that made these achievements possible, and forecast from the increasing rate of invention and discovery an increase in human command over the earth. In particular, he gave evidence that the tropics and arctic regions were not uninhabitable by man, and might become a new human dominion. He believed that his "time only may rightely bee called the liberall and flourishing age," because science and technique, "especially now in these later dayes," had been so much improved "by continuall practise, and the exercising of good wittes," that the "pleasure and profite" of the world was rapidly increasing. He instanced printing, the compass, and navigation as inventions that had transformed human knowledge, and he believed others equally potent could be found.

The most famous exponent of the new optimism in the possibilities of technique was Francis Bacon. He was born in 1561. His father was one of Elizabeth's great statesmen, and he and his brother, Anthony, were educated for the law. Anthony Bacon secured for Richard Boyle the introductions which assisted him to make his fortune and provide the means that his son, Robert Boyle, later put to such good use for science.

Bacon was obstructed in his career by his kinsman Lord Burleigh, who wished to promote his own son, Robert Cecil. He was conscious of his extraordinary talents, which increased his ambition. After the death of Elizabeth, he secured promotion by obsequious attention to the Duke of Buckingham, James I's favourite. He was appointed Lord Chancellor in 1618. James had evaded the recall of Parliament since 1614, and in 1621 the demand could no longer be withstood. The infuriated Parliamentarians indirectly attacked the king by exposing irregularities in the conduct of his Chancellor. Bacon was convicted of bribery, and dismissed. The elucidation of this affair is not simple. Bacon believed in dictation in favour of the poorer classes, whereas his chief opponent, Coke, was the leader of the bourgeoisie, and believed in government by the commercial and landed oligarchy. Bacon was not scrupulous with money, but was concerned with profound political problems. Coke was very scrupulous, but shallow-minded. His copy of the *New Organon* was inscribed with the lines:

> It deserveth not to be reade in Schooles,
> But to be freighted in the Ship of Fooles.

Bacon was insensitive on questions of personal morality, but his conduct is not adequately summarized by Pope's "wisest, brightest, meanest of mankind." The qualities of his opponents were different, but equally unbalanced.

Bacon dictated a tract, *Of the Interpretation of Nature*, some time in 1603, the year of Elizabeth's death. The manuscript, with corrections in his small, firm handwriting, is in the library of the British Museum. It contains the leading ideas of his later writings. He notes in it that his age is distinguished by "the opening of the world by navigation and commerce, and the further discovery of knowledge." He believes that these techniques have cured the limitations of the home-bred wits of primitive man. Speaking in the *New Organon* of the human need to conquer nature, he says: "Even if the breath of hope

which blows on us from the New Continent were fainter than it is and harder to perceive; yet the trial (if we would not bear a spirit altogether abject) must by all means be made." He found that "there is hope enough and to spare, not only to make a bold man try, but also to make a sober-minded and wise man believe." He considered what this hope might inspire. "To speak plainly and clearly, it is a discovery of all operations and possibilities of operations, from immortality, if it were possible, to the meanest mechanical practice." He expresses this aspiration in the *Interpretation*. In the later *New Atlantis*, he says that "the end of our foundation is the knowledge of causes, and secret motions of things; and the enlarging of the bounds of human empire; to the effecting of all things possible."

Bacon adopted the method of a lawyer in pleading for this programme. He attempted to justify it by appeals to the beliefs of his readers. He attempted to show that it had been forecast in Biblical prophecies, and could be convincingly deduced from the dogmas of the Christian religion. He suggested that Daniel's prophecy that "many shall pass to and fro, and science shall be increased," referred to his own times. One may make a quite different deduction from it. Had Daniel in his Babylonian experiences noted that science was born of commerce and navigation? Were the agents that produced science in Babylonia analogous to those that were producing science in the sixteenth century?

Bacon thought that "howsoever" Daniel's prophecies may be, "religion should clearly protect all increase of natural knowledge" because it leads to the greater exaltation of the glory of God, and because it is "a singular help and a preservative against unbelief and error." The value of studies of archaeology and prehistoric anthropology is of interest in connection with this opinion. These studies provide the best ground for optimism concerning the future of humanity. They show that man has survived perils vastly greater than any that af-

flict modern society, and one may justly hope that the worst modern problems will be solved with much less difficulty than many of the problems successfully solved by prehistoric man.

As God "hath set the world in man's heart," man has been specially fitted to understand it. Having received "so large a charter from God," he must put it to the use "for which God has granted it, which is the benefit and relief of the state and society of man."

"And therefore," he says, "it is not the pleasure of curiosity, nor the quiet of resolution, nor the raising of the spirit, nor victory of wit, nor faculty of speech, nor lucre of profession, nor ambition of honour or fame, nor inablement for business, that are the true ends of knowledge." Some of these are more worthy than others, but all are inferior to the true end, which is the restitution of man to his state before the fall. Science and technology are to be used to restore man to the condition of Adam, who was created lord of the world. Bacon's confidence in these agents was such that he did not forbear to hope that they would reveal how life might be made immortal. Compared with this, pure curiosity was a trivial motive for the pursuit of science. "And therefore knowledge, that tendeth but to satisfaction, is but as a courtesan, which is for pleasure, and not for fruit or generation." Knowledge "that tendeth to profit or glory, is but as the golden ball thrown before Atalanta . . ." to hinder her in the race. Particular in contrast with general theory is like Harmodius, who put down one tyrant, rather than Hercules, "who did perambulate the world to suppress tyrants and giants and monsters in every part." Though man cannot, as yet, escape the curses of death and labour, he can use the latter for the restitution of man's state. Bacon drafted a plan and proposed a method for accomplishing this. He named his plan "The Great Instauration"; that is, the restoration of man from his fallen state to his original leadership of the world, as described in the Biblical account.

The Great Instauration was to be composed in six parts, con-

taining an enumeration of the sciences, a method for interpreting nature, a natural history of the universe as a foundation for science, an improved method of intellectual analysis, anticipations of the new philosophy, and an exhibition of the new philosophy. Bacon completed the second part under the title of the *New Organon,* and made notes for some of the others, but he said that the completion of the sixth part, to which the others were preparatory, was above his strength and beyond his hopes. But he had made a beginning, and "the fortune of the human race will give the issue." He believed that this might be extraordinary beyond the present imagination of men. "For the matter in hand is no mere felicity of speculation, but the real business and fortunes of the human race. For man is but the servant and interpreter of nature: what he does and what he knows is only what he has observed of nature's order in fact or in thought; beyond this he knows nothing and can do nothing. For the chain of causes cannot by any force be loosed or broken, nor can nature be commanded except by being obeyed. And so those twin objects, human Knowledge and human Power, do really meet in one; and it is from ignorance of causes that operation fails."

No excellence of method could supply the mind with the material of knowledge. Those who did not aspire to guess the divine but to discover and know "must go to facts themselves for everything." This labour could not be replaced by any genius or meditation, "no, not if all men's wits could meet in one."

He believed that Democritus and the Ionian Greeks had a deeper insight than Pythagoras and Plato into the nature of science. He noted that philosophies of the Platonic type appealed to the "ambition of the understanding," and did not improve upon the model. In them "the proceeding has been to fly at once from the sense and particulars up to the most general propositions" and to deduce various consequences from them. "A short way, no doubt, but precipitate; and one which will

never lead to nature, though it offers an easy and ready way to disputation." He proposed to use a new form of induction in which he would proceed from one axiom to another, so that the most general notions would not be reached until the last. It was different from the logician's induction, "which proceeds by simple enumerations" and "is a puerile thing." His induction would "analyse experience and take it to pieces, and by a due process of exclusion and rejection lead to an inevitable result."

Science could not be based merely on sense-impressions and empirical information, for sometimes the senses gave no information or false information. He had therefore sought "to provide helps for the sense," and had endeavoured to do this by the use of experiments rather than instruments.

The eye was subject to illusions, and the constituents of things were beyond the resolving power of the most powerful microscopes. But "the subtlety of experiments is far greater than that of the sense itself, even when assisted by exquisite instruments," if the experiments were skilfully devised to test the point at question. He did not give much weight to the immediate perception of sense, but contrived "that the office of sense shall be only to judge of the experiment, and that the experiment itself shall be the judge of the thing."

His improved form of induction, assisted by experiment, would be sufficient to interpret nature if the mind itself were not defective. But the innate ideas, and those that entered the mind from without, distorted its operation, and made it "far more prone to error than the sense is." The intellect must be purged to enable it to qualify for dealing with the truth. The false ideas entering it from the old philosophies must be refuted. The logical method must be improved, and allowance must be made for the effect of innate ideas that could not be eradicated. When this had been done, the "lawful marriage between the empirical and the rational faculty" would have been established forever. His method "is not an opinion to be held, but a work to be done." He aimed at the invention of technique and not of

arguments. He did not try to deduce the nature of things from principles, but to discover general principles from things. The former method enabled one "to command nature in action," for axioms, or scientific laws, "once rightly discovered," led to results "not here and there one, but in clusters."

Bacon followed the inspiration of the development of machinery. He had noted that the mechanical arts had "in them some breath of life," and were "continually growing and becoming more perfect," whereas philosophy, on the contrary, stood like a statue, worshipped but not advanced. He wanted to introduce into mental operations a quality of growth analogous to that observed in technique, and he believed it could be done if the mind was given suitable tools, as the naked hands of the craftsman are assisted by tools. He wanted "the entire work of understanding to be commenced afresh," and provided with a method that would enable it to proceed "as if by machinery." His philosophical method was parallel to the machine. As the machine assisted the mechanic of moderate gifts to do good work, so his philosophical method, or machine, would enable persons of moderate intellect to make useful contributions to science. As for his own work, it was a child of the times "rather than of wit." He was merely a guide "to point out the road; an office of small authority, and depending more upon a kind of luck than upon any ability or excellency." He had happened to appear at a strategic moment in the history of science. Time would show that those who joined him in the use of his method, which consisted not of extracting "experiments from experiments [as an empiric], but from works and experiments to extract causes and axioms, and again from those causes and axioms, new works and experiments," would reveal technical inventions as remarkable as the "new-found world of land." Existing science would seem as barbarous compared with the new inventions as the inhabitants of the New World appeared in comparison with those of the Old.

He wished that the "arts and sciences should be like mines, where the noise of new works and further advances is heard on every side." If one turned "from the workshop to the library," he would be astonished at the "poverty and scantiness of the subjects which till now have occupied and possessed the minds of men," when compared with the admirable variety of products in the former. One should introduce the methods of the workshop and the mine into mental operations.

But other agents were also necessary for the progress of science. "Efforts in this field go unrewarded," because those who advanced science were great wits, while the rewards were "in the hands of the people, or of great persons," who were generally not learned, and could not understand their achievements. For the same reason, scientists did not even receive popular applause. "And it is nothing strange if a thing not held in honour does not prosper."

But he considered that men's tendency to "despair and think things impossible" was "by far the greatest obstacle to the progress of science."

Bacon gave one illustration of his method. He applied it to the analysis of the nature of heat. He made a list of phenomena exhibiting heat, including the sun's rays, meteors, flames, hot solids, liquids and vapours; "all bodies rubbed violently," quicklime dissolved in water, oils that burn the teeth, alcohol that hardens the white of eggs, herbs that burn the tongue, etc.

Then he made a list of phenomena, parallel, item by item to those in the first list, in which heat was absent. These included moon rays, "rotten wood, which shines by night, and yet is not found to be hot," the *ignis fatuus*, the sparkle in sea water when struck by oars at night, etc. He could not think of any body whose heat was not increased by attrition. The ancients had fancied that the stars were heated by attrition of the air. He would like experiments made to see whether cannon balls were heated by attrition of the air. Wind, or air in motion chills, but

"motion of this kind is not so rapid as to excite heat, and is the motion of a mass, and not of particles; so that it is no wonder if it does not generate heat."

His third step consisted of an analysis of the degree of heat in the bodies itemized in the previous lists. He noted that "in solid and tangible bodies we find nothing which is in its nature originally hot." Animal heat was increased by motion and exercise. The heat of the heavenly bodies was never great enough to set fire to wood or straw, but "it is, however, able to extract vapour from moist substances." There were many degrees of strength in the heat of flames, but that of powerful lightning exceeded all others, for it melted "wrought iron into drops, which those other flames cannot do."

Motion increased heat, as might be seen in the use of furnace bellows. "An anvil grows very hot under the hammer, insomuch that if it were made of a thin plate it might, I suppose, with strong and continuous blows of the hammer grow red like ignited iron. But let this be tried by experiment," etc.

He then applied his method of induction to the facts in these three lists. He rejected in each item qualities not present in it, and therefore responsible for its heat, though they might be present in other hot items. As the sun's rays were hot, heat could not be matter. Heat could not be of the same nature as the heavenly bodies because common fires were hot. Heat could not be light, because boiling water and other dull substances were hot. As iron did not visibly swell when heated, heat could not be due to the expansion of the body as a whole. Heat could not have a destructive nature because all bodies were heated so easily. Heat could not exist in the nature of things positively, as, "on account of heat being kindled by the attrition of bodies," it was the effect of an "antecedent nature."

Bacon now abstracted those features of heat common to all the items. He said: "From a survey of the instances, all and each, the nature of which Heat is a particular case appears to be Motion. This is displayed most conspicuously in flame . . .

it is quite clear that heat causes a tumult and confusion and violent motion in the internal parts of a body, which perceptibly tends to its dissolution." He noted that "heat is one thing, heating another," as "heat is produced by the motion of attrition without any preceding heat." He concluded "that heat is a motion of expansion, not uniformly of the whole body together, but in the smaller parts of it. . . . Heat is a motion, expansive, restrained, and acting in its strife upon the smaller particles of bodies."

Bacon gave only one example of the application of his method, but it was remarkably successful, for it led him to propose the dynamical theory of heat.

His method was not the same as that used by Copernicus, Gilbert, Galileo, and their successors. He was critical of their achievements. He complained of Gilbert that after he had most laboriously investigated the properties of magnetism, he "proceeded at once to construct an entire system in accordance with his favourite subject." Galileo's observations of Jupiter's satellites, etc., were "all indeed noble discoveries," but he regarded demonstrations of this kind with suspicion, because "the experiment stops with these few discoveries, and many other things equally worthy of investigation are not discovered by the same means." He explained that the advance of learning was impeded by the splitting of special sciences from universal knowledge. The specialists lost a broad perspective, and were unable to correct theories consonant with their own science, but not with the general background of knowledge. For this reason, he opposed Copernicus' theory, because it was repugnant to general experience, though consistent in itself. He rejected Galileo's theory of the tides, which was based on the supposition of relative motion between the seas and the rotating earth, because he did not believe the earth moved.

He believed there was a connection between the moon and the tides, and that it was due to actions operating at great distances. He believed that these powers which act at distances are

"all finite and fixed in the nature of things," and their limits are set by "the mass or quantity of matter in the bodies acted on," or by media, or other agencies. In the same paragraph he suggests that the so-called violent motions, such as those of projectiles, guns, wheels, etc., also have their fixed limits, or definite values, which "should be observed and computed."

It is evident that Bacon's method and the scientific method first comprehensively practised by Galileo are not identical. In spite of his insistence on the need for studying and performing mechanical operations, he did not appreciate that this was necessary to assist the imagination to make a picture of the process, besides providing the memory with a record of the particulars of the process. He believed he could derive the law of a scientific process from a logical analysis of its particulars without the aid of a picture or formula. While he said that "inquiries into nature have the best result when they begin with physics and end in mathematics," he also said that mathematics should "only give definiteness to natural philosophy," and should not "generate or give it birth." He had in mind the Platonists and Pythagoreans, who believed they could deduce the properties of nature from numerical speculations and coincidences. These views were sound, but he did not fully understand that physical facts should be resumed in mathematical formulae, from which the existence of hitherto unknown facts could be calculated. Nevertheless, his method was capable of giving a very remarkable result, as is seen in his proposal of the dynamical theory of heat. He did in fact use his pictorial imagination in arriving at this result, but he was unaware that he had invented in his imagination the picture of heat as a motion of constituent particles before he had seen that this phenomenon was consistent with all of the manifestations of heat enumerated in his list. The Baconian induction was strongest when a simple picture was to be derived from many facts. It was successful in deriving the dynamical theory of heat, and Darwin used a similar method in deriving the theory of evolution

from a multitude of biological particulars. It was weakest when a detailed picture was to be derived, and described in a mathematical formula.

Bacon was inclined to give more weight to logic than to experiment, but he proposed and made many experiments. He suggested that the time kept by a clock at the top of a steeple and at the bottom of a mine should be compared, to find whether "we may take the attraction of the mass of the earth as the cause of weight."

He had found that the specific gravities of all solids and liquids lay within a ratio of 1 to 21; "so limited is nature, or at any rate that part of it with which we have principally to do." He investigated the ratio of the specific gravities of vapours to liquids. He completely filled a glass phial which would hold about one ounce of liquid with alcohol. He weighed the filled phial, and tied a flattened bladder to its neck, so that there was no free space over the liquid. He placed the phial on a chafing dish of hot coals. The alcohol began to evaporate, and presently filled the bladder, and he pricked the latter before any of the vapour could condense. He measured the quantity of alcohol lost from the phial, and as he knew the volume of the bladder, he could calculate what volume of vapour was obtained from the volume of the lost liquid. He "computed the results; which showed clearly, that the body had required by the change a degree of expansion a hundred times greater than it had had before."

Bacon showed by experiment that water is virtually incompressible. He filled a leaden sphere with water, sealed it, and had it heavily pressed. The water "exuded through the solid lead like a fine dew," and the deformation of the sphere was slight, so he concluded that water resists compression.

Bacon was not an incapable experimenter.

Besides restating the aim of science, and elaborating a method of research, Bacon described in his fable, the *New Atlantis*, an organization for advancing science. He imagined an undis-

covered island in the Pacific, named Bensalem, whose inhabitants had organized a rational society based on advanced science and technique. They concealed their existence from the rest of the world to prevent the incursion of less civilized people, but they sent out secret expeditions to acquire all new knowledge.

The institute that organized the rational society and research was named Solomon's House. Its members were named fellows, and had specific duties. Twelve sailed secretly into foreign countries, to bring information of books and plans for experiments. Three fellows made notes of all experiments recorded in books. Three collected all information on mechanical crafts and experimental science, and on processes not yet adopted by the crafts. Three fellows "try new experiments," and another three analyse their results and attempt to deduce new laws from them. Three fellows consider how these new laws and results may be applied to "use and practice for man's life and knowledge."

All of the fellows discuss together the results of this programme, and three more consider what new lines of research are suggested by them. Yet another three fellows follow these new lines; and finally, there are three who extract the most general conceptions from the previous activities, and are named "interpreters of nature."

The fellows were assisted by a staff of apprentices, or research students, and a large number of assistants.

Their house had "two very long and fair galleries," with statues of the principal inventors and discoverers. "There we have the statue of your Columbus, that discovered the West Indies," and of the inventors of ships, ordnance, music, writing, printing, astronomy, metals, glass, silk, wine, corn, sugar, etc. The inventor of any valuable new process is given "a liberal and honourable reward."

The growth of commerce and discovery, which had directed Bacon's interest towards science, impelled many more men in

the same direction during the first half of the seventeenth century. When these men came together, and sought for a means of incorporating their interest, they followed Bacon's plan for a Solomon's House. They formed a society of scientists, and tried to organize its activities according to Bacon's pattern. This society presently became the Royal Society of London, and its members are named fellows, after the Baconian title.

The duties of the fellows of Solomon's House were not restricted to their headquarters. They had "circuits or visits of divers principal cities of the kingdom; where, as it cometh to pass, we do publish such new profitable inventions as we think good." This was the pattern of the British and American Associations for the Advancement of Science, realized two centuries later.

There is much confusion concerning Bacon's contribution to science. The professional scientist notices the limitations in his scientific method and his inability to make many discoveries. And yet it is generally felt that Bacon's scientific writings are very important. This is quite correct. It is evident that the core of Bacon's work was not science, but the social relations of science, and that he was virtually the first, and a very great, writer on this subject. Nor have later scientists entirely neglected his notion of a general method of discovery. Pierre Curie, in his deduction of piezo-electricity from considerations of symmetry, was moving in that direction.

Bacon's criticisms of Gilbert, Galileo and Copernicus are not so unfounded as is generally supposed. Bacon was aiming at the invention of a method which would not only solve particular scientific problems, but also solve the adaptation of the results to the social process. He did not greatly esteem Galileo's method of abstracting problems entirely from their general and social context. But the narrowness of Galileo's method, which was exposed by his inability to understand the nature of his conflict with the Church, was nevertheless not generally appreciated until recent times. Scientists have followed Galileo for

three centuries, piling up discoveries in regions of research artificially isolated from the general body of knowledge and social affairs. The fate that overcame Galileo is now, in the present catastrophes, overcoming the scientists who have followed him. They, like him, have failed to understand the relations between science and society, so they are being crushed.

Harvey said that Bacon wrote on science like a lord chancellor. It may be retorted that Harvey wrote on science like a scientist, in the limited Galilean sense.

If scientists are to save themselves now, they must no longer be pure Galileans, but become also Baconians, and remember that "knowledge, that tendeth but to satisfaction, is but as a courtesan," and its proper use is for "the benefit and relief of the state and society of man."

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THE MAYOR OF MAGDEBURG

Magdeburg owed its importance to its site on the river Elbe. The trade between northern and southern Germany crossed the river most conveniently by the city and the trade between east and west naturally travelled along the river to Hamburg and the North Sea. Owing to these connections, Magdeburg was a member of the Hanseatic League. The city was only one hundred miles from Chemnitz, the centre of the mining industry so well described by Agricola. It was on one of the routes by which the precious metals and other products of this industry were transported to Holland, the centre of the commercial world in the seventeenth century. Magdeburg was of strategic importance in the Thirty Years' War.

The Catholic armies under Tilly and the Protestant armies under Gustavus Adolphus both wished to possess it. In 1631 Tilly threatened it with siege if it did not surrender. The mass of the population were strongly Protestant and wanted to resist, but a section of the rich men who governed the city, though Protestant, feared the destruction of their wealth, and wished to make terms with Tilly. Gustavus Adolphus was very anxious that Magdeburg should resist, because it provided him with a bridge across the Elbe and access to the south. He was unable to send reinforcements and munitions immediately, and in fact desired to borrow the city's own military store. He offered them in return promises of extensive future help. When the city councillors showed unwillingness to accede to this request and to compromise with Tilly, Adolphus' agents threatened to appeal to the citizens over their heads. The council

then decided to lend their stores to Adolphus. Tilly advanced on the city, but Adolphus was still unable to come to its aid. The defence of the city, with its depleted stores, fell mainly on the citizens, under the military leadership of a Swedish general. Two defence officers were appointed by the city council, one of whom was Otto von Guericke. This young man belonged to a leading family in the city. He was born in 1602, and was twenty-nine years old when appointed officer of defence.

He had been prepared from his youth to take part in the government of the city. He was an only son of wealthy parents and every aid was lavished on him. He had been sent at the age of fifteen to study law at the University of Leipzig, and continued his studies at Helmstedt and Jena. He was then sent to Leyden, where he attended lectures on science and military engineering. Military science was often the core of university science courses at that date. The separation of physics, chemistry and biology courses, as known today, came at a later date.

He visited England and France and returned to Magdeburg when he was twenty-three. He had married, and immediately became a leading citizen.

As defence officer and military engineer, he designed fortifications and armaments and superintended their construction. The lack of stores, and especially of gunpowder, was very serious, so he organized the manufacture of powder from the supplies of nitre in the single apothecary's shop in the town.

In spite of his energy and ability, Magdeburg fell, as Gustavus Adolphus failed to come to its aid, and it could not hold out long against Tilly's superior forces. The city was burned and completely destroyed. Guericke nearly lost his life, and all his property. He was saved through the intercession of a leading citizen who happened to be friendly with one of Tilly's generals, and he and his family were presently ransomed by the Protestant friends of Magdeburg.

After his release, Guericke was appointed Quartermaster General to Gustavus Adolphus, following the example of Stevin

in becoming the technical organizer of resistance by the Protestant leaders of commercial powers against the Catholic landed and financial powers.

Gustavus counter-attacked, and presently recaptured the site of Magdeburg. After this had been achieved, Guericke was released from his quartermaster generalship, and returned to supervise the reconstruction of the city. He designed new bridges, fortifications and buildings, besides taking a leading part in politics. As the city was poor, it could not pay him enough for a livelihood, so he had to increase his income by farming and brewing.

He was appointed a burgomaster of the city in 1646, and retained a leading official position the rest of his long life, which ended in 1686.

Much of his time was given to diplomatic negotiations on behalf of the city at Vienna, Prague, Regensburg and other capitals.

Guericke's early training in, and continual practice of, science and engineering continually kept the problems of the properties of matter before him. While he kept this aspect of nature in mind, he also followed the scientific discussions of the day on the structure of the universe.

He tried to interpret theology by combining his scientific and religious interests. He attempted to determine the location of heaven and hell, and to harmonize Joshua's account of the suspension of the motion of the sun with the Copernican theory. These problems brought him to the consideration of the properties of outer space, which he supposed was a vacuum. How could he obtain a piece of vacuum and see what the properties of outer space, and of heaven and hell, were like?

As an experienced executive engineer and a man who had acquired the habit of solving problems by action and improvised research, he approached the problem of the vacuum in an active practical attitude. He decided to try to make a vacuum, and investigate its properties by experiment, besides

speculation. He was accustomed in his brewery to handle liquids and gases and to use pumps, and he knew how to empty trenches and put out fires, which also involved knowledge of pumps. A good deal was known about these at Magdeburg, owing to the proximity of the city of Chemnitz, the centre of the region where miners had been forced to learn much about pumps, and had acquired more knowledge of this branch of engineering than was possessed by any other group of engineers in the world.

Guericke conceived the plan of filling a vessel completely with water, and then removing the water with a suction pump. He thought that if the water could be removed, a vacuum would be left in the vessel. He filled a wooden barrel from his brewery with water, and then tried to pump out the water with a suction pump, which consisted of a barrel about one foot long and several inches in diameter, with a piston that could be drawn out directly by hand.

The defender of Magdeburg, who had no doubt put out many fires during the siege of his city, was probably very familiar with fire-engines. It is not surprising that he adapted the force pump of a fire-engine, which acts as a suction pump on the inlet stroke, for the removal of the water from the barrel. He found that after the first few strokes, great force was needed to pull out the piston, and he had to strengthen all the joints and fastenings. But he found that with three strong men hauling on the piston, the water could be removed.

A noise came from the barrel as if the remaining water were boiling, and it was noticed that air was leaking in—a phenomenon ever since so familiar to employers of vacuum technique. Guericke covered the barrel with pitch to stop the leaks, and repeated the removal of water, but again the air leaked through the crevices even when covered with pitch. He then submerged the whole barrel in water, and found the leakage was much reduced. But this was still unsatisfactory, so he made a roughly spherical large copper vessel which would not leak.

He did not bother to fill it with water, but attached the pump to it directly, and found the air inside could be directly removed. When the sphere was nearly exhausted, it suddenly collapsed with a loud report. Guericke at once perceived that it had collapsed owing to its imperfect sphericity, so he made a more perfect copper sphere. This did not collapse after exhaustion. He found that when the stopcock was opened, air tore in with great force. His skill in handling large copper vessels was derived from his experience in his brewery.

He now constructed "a special machine for making a vacuum." This was the first air pump. He recognized the necessity for preventing leaks and reducing the amount of dead space inside the pump to a minimum.

He began a long series of entirely new investigations with this machine. He used glass spheres with wide necks and ground joints for observing vacuum effects. He found that the smallest quantity of air was expansible beyond the limits of observation. He noted that when the air was being exhausted, it expanded of itself into the pump cylinder. He noted the rapidity with which equalization of pressure occurs in a long tube that is being exhausted, and observed that the gusts of air were sufficient to blow bolts and nuts along the inside of the tube. He deduced from this that atmospheric storms are due only to differences in air pressure, and forecast a big storm from a big drop in atmospheric pressure. He noted the clash of water inside a vacuum, which produces the water-hammering effect. He directly measured the specific gravity of the air by weighing a glass globe full and exhausted, and recognized that the result depended on pressure and temperature.

He showed that light could travel through a vacuum, but sound would not. He found that candles went out, and animals died, when placed in a vacuum, and he concluded that fire obtains something from the air which enables it to support combustion. He enclosed a burning candle in a volume of air held over water, and found that the candle consumed one-tenth of

the air before it was extinguished. His large-scale experiments with vacua were not less remarkable. He showed that even fifty men could be hauled by a piston in a cylinder which had suddenly been connected with a large vacuum chamber. He constructed large hemispheres which required teams of twenty-four horses to pull them apart when exhausted, but which fell apart without effort when air was let in by opening a tap.

Guericke first made these experiments at Magdeburg about 1650. He was appointed diplomatic representative of the city at the Reichstag at Regensburg in 1654, and it is said that he repeated the experiments before the Emperor of Germany and the assembled princes, though this has been questioned.

His diplomatic task was to secure the freedom of Magdeburg from ducal protection. The demonstration of the "Magdeburg Hemispheres" at Regensburg, if it did occur, was no doubt intended to secure prestige for Magdeburg by exhibiting the genius of its citizens, and thus secure favourable consideration of her diplomatic aims. It was a form of cultural propaganda. There is little doubt, too, that Guericke was proud of his own ingenuity. His apparatus was expensive in spite of the workshop resources of his brewery, and he increased its cost by decorations with precious inlaid ornaments. This attempt to use science as a means for political propaganda failed. Guericke did not secure the freedom of his city, though he increased his personal fame.

His researches were not restricted to vacua. He constructed the first electrical machine. It consisted of a large ball of sulphur which could be rotated on a horizontal iron axis by a crank.

Electrification was produced by holding the hand against the sulphur sphere while it was rotated. The engineering scale of this machine was again of fundamental value, and provided results that could not be obtained with small laboratory apparatus.

He could create large electric charges, and these enabled

him to discover the phenomenon of electrical repulsion. With a copy of Guericke's machine, Leibnitz in 1672 consciously produced electric sparks for the first time.

Robert Boyle first heard of Guericke's invention of the air pump in 1657. With Hooke's assistance he immediately constructed an improved pump, and began a series of experiments described in his book on *New Experiments Physico-Mechanical Touching the Spring of the Air*. This contains three hundred pages, and the experiments and their description were completed in two years.

Boyle made many experiments on flames and animals in air under reduced pressure, and approached the discovery of oxygen. He noted the view of Paracelsus and Drebell that "it is not the whole body of the air, but a certain quintessence or spirituous part of it, that makes it fit for respiration." He was favourable to this opinion, "for we see, that in our engine the flame of a lamp will last almost as little after the exsuction of the air, as the life of an animal . . ." and "our engine thus shows us a new kind of resemblance betwixt fire and life." Experiments on the dissolved air in water, which is released by reducing the pressure, led him to conjecture "that there is wont to lurk in water many little parcels of interspersed air, whereof it seems not impossible that fishes may make some use."

He observed the boiling of warm water at reduced pressure, and deduced from it "that the air, by its stronger or weaker pressure, may very much modify (as the schoolmen speak) divers of the operations of that vehement and tumultuous agitation of the small parts of bodies, wherein the nature of heat seems chiefly if not solely, to consist."

He discussed the expansion of air as evidence for the atomic constitution of gases, and while writing with keen interest, excuses himself from offering an answer, as the question is so difficult.

His account of the experiments, which was published in 1660, when he was thirty-four years old, was adversely criticized by

Hobbes and others. In a second series of experiments to confirm and extend the first, he described the discovery and proof of the celebrated law named after him.

The air pump is the most important technical invention in the history of science, because it provides a means of investigating gases, which present the phenomena of matter in their simplest form. As the human body is not a good material on which to start the investigation of nature, because it is too complex, so solids and liquids are at first less helpful than gases as guides to the constitution of matter. The expansibility of gases made their atomicity seem probable, and the law discovered by Boyle provided the data for the first successful deduction from the atomic hypothesis by mathematics. This was made by Newton when he showed that Boyle's law could be mathematically deduced from the atomic hypothesis.

The successful deduction converted the atomic hypothesis into a scientific theory, and provided a theoretical foundation for chemistry. John Dalton recorded that he drew his inspiration from Newton's incursion into the atomic theory of gases.

Guericke's spectacular experiments with the big hemispheres revealed the possibility of a new source of power. For the first time since the harnessing of water and wind, a new motive was discovered. Newcomen succeeded in harnessing the power of the vacuum by his steam engine, and this led to the development of steam power.

The study of the steam engine produced the science of thermodynamics, and this, when combined with the atomic theory of gases, produced statistical mechanics and the quantum theory.

The investigation of the electrical properties of gases at low pressure, made possible by Guericke's air pump and his electrical machine, led to the discovery of the electron and the electrical constitution of matter.

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THE FATHER OF CHEMISTRY AND UNCLE OF THE EARL OF CORK

Robert Boyle remarks at the end of his first book on the spring of the air that though he had intended it to be only a short letter describing his results, it had expanded into a volume, "yet the experiments already mentioned in it are so far from comprising all those that may be tried by the help of our engine, that I have not yet been able to try all these, which, presently occurring to my thoughts, upon my first seeing the working of it, I caused to be set down in a catalogue within less than half an hour."

Boyle here reveals the most important part of scientific method. It consists of the invention of a new instrument or technique. When this has been done, the subjects for a lifetime of research may be written down in less than half an hour. Speculation is idle until the experimental means of testing it have been invented.

The experimental means were derived from the mechanic's workshop. The air pump constructed by Hooke and Boyle was about three feet over all. Its size was typical of the industrial machines of the day, and the sort of skill required to handle it depended on practical acquaintance with the mechanical processes by which it had been constructed.

Boyle was aware of the necessity of studying industrial processes in order to acquire the orientation which sets the mind towards experimental discovery, and he discussed the problem repeatedly. He advocates in his long treatise on the Usefulness of Natural Philosophy the need for personal experi-

ment, even with the most disagreeable materials. He says that he is not too squeamish to experiment on the nature and use of dungs. "And though my condition does (God be praised) enable me to make experiments by others' hands; yet I have not been so nice, as to decline dissecting dogs, wolves, fishes, and even rats and mice, with my own hands. Nor, when I am in my laboratory, do I scruple with them naked to handle lute and charcoal." He explains that natural philosophy teaches not only the knowledge of nature, but "in many cases to master and command her." The true scientist not only knows many things which other men ignore, "but can perform many things which other men cannot do," and is enabled by his skill "not barely to understand several wonders of nature, but also partly to imitate, and partly to multiply and improve them." He discusses the usefulness of mathematics and of mechanics to natural philosophy and explains "that the Goods of Mankind May be much increased by the Naturalist's insight into Trades." He says that he will show that "insight into trades may improve the naturalist's knowledge," and that the naturalist, "as well by the skill thus obtained, as by the other parts of his knowledge may be enabled to improve trades." He agrees that industrial processes are a part of the history of nature. It will not "suffice to justify learned men in the neglect and contempt of this part of natural history, that the men from whom it must be learned are illiterate mechanics. . . ." This social objection, he says, "is indeed childish, and too unworthy of a philosopher, to be worthy of a solemn answer." He believes that the progress of natural philosophy has been hindered by the haughtiness and negligence and "superciliousness and laziness" too often learned in "schools." These social attitudes have damaged the true interest of mankind by keeping "learned and ingenious men . . . strangers to the shops and practices of tradesmen."

The phenomena of industrial processes are particularly instructive because they show nature in motion, and "that too, when she is (as it were) put out of her course, by the strength

and skill of man, which I have formerly noted to be the most instructive condition, wherein we can behold her."

He recommends scientists "to disdain, as little as I do, to converse with tradesmen in their work houses and shops," and takes leave to say that "he deserves not the knowledge of nature, that scorns to converse even with mean persons, that have the opportunity to be very conversant with her." The scientist may often obtain very instructive information from those "that have neither fine language nor fine clothes to amuse themselves."

Craftsmen have a thorough knowledge of the materials they handle because they lose trade if their products are inferior. Owing to "want of subsistence," their wits are sharpened, and they are forced to invent more economical tools and processes, for "necessity" was ever "the mother of invention." He had noticed that craftsmen are familiar with many substances not mentioned by the classical authors, and he records that he has "learned more of the kinds, distinctions, properties and consequently of the nature of stones, by conversation with two or three masons, and stone-cutters, than ever [he] did from Pliny or Aristotle, and his commentators."

Craftsmen's theories and opinions were based on frequently repeated experiences, whereas scholars usually restricted themselves to a few experiments. As craft was often passed down from father to son, a family might learn of slow effects, which may take twenty years or longer to develop, and which could not be noticed in a short experiment. He wished to "carry philosophical materials from the shops to the schools." He desired gentlemen and scholars to converse with tradesmen, for "it will qualify them to ask questions of men, that converse with things." From this knowledge of the processes of craftsmen, scientists should be able "to meliorate the inventions of illiterate tradesmen." He considers "that in many cases, a trade differs from an experiment not so much in the nature of the thing, as in its having had the luck to be applied to human uses,

or by a company of artificers made their business, in order to their profit, which are things extrinsical, and accidental to the experiment itself."

Boyle describes scientists like himself as "commercers with nature." He exhibits the introduction of the psychology of the trader into man's attitude towards nature. The scientist approaches nature in the attitude of an entrepreneur.

Mathematics and mechanics are useful to him because they assist him "to frame theories, or to make observations and experiments." The study of geometry and machinery, with their "lineal schemes, pictures and instruments, assist the imagination to conceive many things, and thereby the understanding to judge of them, and deduce new contrivances from them."

He explains that one of his motives for studying nature is his ardent desire to benefit his fellow-men, and he believes that natural philosophy should "afford them both curious flowers to satisfy their curiosity, and delight their senses, and excellent fruits, and other substantial productions, to answer the necessities, and furnish the accommodations of human life."

Boyle acutely criticized the Aristotelian theory of the elements, which had been accepted for two thousand years. He said that he could "not look upon any body as a true principle or element, which is not perfectly homogeneous but is further resolvable into any number of distinct substances." He first propounded the modern theory of chemical elements, and also of systematic chemical analysis. He believed that "matter and motion" were the most primary "principles of things," and directed scientific thought towards atomic theory.

Boyle's effort to establish the social repute of the systematic study of craft and engineering processes, and to break the social barrier between gentlemen and craftsmen, was of the greatest service to science. He and his followers transformed the attitude of the governing class towards the study of nature and annexed the knowledge of craftsmen and engineers for the benefit of this class. Science began to advance rapidly when the

motive power generated by the interests of the governing class was more consciously applied to it. Besides appreciating that successful research depended on the orientation of mind derived from the craftsman and merchant, Boyle explained to his "dear nephew," the heir to the earldom of Cork, that he hoped to "indear" experimental philosophy "to hopeful persons of your quality," because the "effectual pursuit" of it "requires as well a purse as a brain."

The rise of the Boyles to great wealth was very recent, and was accomplished by Richard Boyle, the father of the scientist. The family had been obscure English country gentlefolk for many generations, and Richard Boyle, who was born in 1566, was educated at Cambridge, and had intended to study law but had not the means. He says that he "resolved to travel into foreign kingdoms, and to gain learning, and knowledge, and experience abroad in the world." He sailed for Ireland in 1588, and when he arrived in Dublin "all my wealth was twenty seven pounds three shillings in money," a diamond ring and a bracelet of gold given him by his mother, and some changes of clothes, "with my rapier and dagger."

He married a lady with an estate of £500 per annum in 1595. She died in childbirth in 1599. Richard Boyle records that her inheritance was "the beginning and foundation of my fortune."

He engaged in estate speculations, and his wealth grew rapidly, so rapidly that the jealousy of Sir Henry Wallop, the Lord Treasurer of Ireland, and others was aroused. These influential persons informed Queen Elizabeth that he could not have obtained all this wealth without receiving payments from foreign princes, as he had been poor when he had arrived in Ireland.

A rebellion in Munster postponed the discussion of this matter, and Richard Boyle's land was wasted in the fighting. He returned to London to resume the study of law, and was engaged by the Earl of Essex. When Essex was appointed Governor of

Ireland, Wallop's anxiety concerning Richard Boyle revived. Richard states that he had sundry papers which showed "a great deal of wrong and abuse done to the queen in [Wallop's] late accounts."

Wallop feared that Richard would use these papers to blackmail him, so he again denounced Richard to the Queen, who ordered his arrest. After four months' investigation, he secured his acquittal and recorded later that the Queen had commented: "By God's death, these are but inventions against this young man; and all his sufferings are for being able to do us service, and those complaints urged to forestal him therein. But we find him a man fit to be employed by ourselves; and we will employ him in our service; and Wallop and his adherents shall know, that it shall not be in the power of any of them to wrong him; neither shall Wallop be our treasurer any longer."

The Queen appointed him Clerk of Munster, and he bought Sir Walter Raleigh's ship, the *Pilgrim*, to sail again to Ireland. "And this was the second rise, that God gave to my fortune." He was very active in the suppression of Irish revolts. Some time later Sir Robert Cecil persuaded Raleigh to sell his Irish estate to Richard Boyle, as it was "then altogether waste and desolate." While this powerful politician represented to Raleigh that his Irish estates were virtually without value, Richard Boyle states that through the purchase "my assurances were perfected; and this was a third addition and rise to my estate." He married the only daughter of Fenton, the Secretary for Ireland, who presented him with "one thousand pounds in gold" as a wedding present.

He presently acquired the titles of knight, Lord Boyle, Baron of Youghall, Viscount Dungarvan, and Earl of Cork, and was Treasurer, and one of the two Chief Justices, of Ireland. His estate became "the greatest in the memory of the last age." He built many villages and towns, and his constructions subsequently received Cromwell's praise, who is reported to have said that "if there had been an Earl of Cork in every province,

it would have been impossible for the Irish to have raised a rebellion."

The first Earl of Cork was the richest of the new rich of his age. He had a great eye for business. Though he made his fortune in Ireland, he was not more of an Irishman than Baron von Neurath is Czech.

Robert Boyle was his fourteenth child and seventh son, and was born in 1626 at the great house of Lismore in Munster. He was Irish only by place of birth. He explains that as a younger son of a great nobleman he was in a happy position to pursue scientific studies. He was not called to manage the estate and affairs of the family, and yet he had an adequate income.

He could afford to be pious and kind, independent and even eccentric.

The first Earl of Cork exhibited the mastery of business and common affairs characteristic of the new class of Tudor mercantile noblemen. Robert Boyle's orientation towards crafts was derived from their outlook. His father, in contrast with the feudal nobility, believed that children should be reared simply, on rough but wholesome food. This strengthened their constitutions and gave them some knowledge of the common people and their occupations, which, incidentally, was the best preparation for future business. Robert Boyle had been sent as soon as possible to a peasant nurse and was reared for years in the country. He has recorded his gratitude for this early toughening. He was not over-bred, in spite of his birth and the fineness of his mind. Owing to his fortune, he did not need to use the exploiting habits acquired through his descent to make money.

He could find a more urbane exercise for them in restless acquisition of natural knowledge and in the analysis and improvement of trading processes. His nobility, though very recent, had much influence on science. The ordinary member of his class was too busy acquiring riches to advance beyond the degree of acquaintance with technique necessary for its ex-

ploitation, and had not yet learned to understand and respect it. This could not be done until the new sort of gentleman personally studied crafts and mixed with craftsmen. Only a great nobleman could advocate that without loss of caste. Boyle helped to establish the social repute of craft processes, and thus made the source of experimental science worthy of the personal attention of gentlemen, and of the governing class. As soon as these processes had acquired as much social repute as the mental operations of scholars and gentlemen, practice and theory could be harmoniously combined and so provide the condition for the rapid development of modern science.

Robert Boyle made such an important contribution to this development because he had a strategic social position. He became "the father of chemistry" because he was the son of his father, and "uncle of the [third] Earl of Cork," besides having great talent.

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62

THE ROYAL SOCIETY

When the dominance of the mercantile classes became confirmed, their interests determined the perspective of intellectual and other endeavour. The problems of trade and manufacture were accepted as of the highest importance. They were studied by those directly engaged in them, and by others who derived incomes from them even if not directly engaged. Thus men of business and leisure were interested in the same problems. A sharp division between the trading and the leisured classes could not be drawn. Traders meditated on the scientific aspects of their problems in working and leisure hours, and men of leisure dabbled in inventions which they thought might draw big dividends.

Men with these interests had occasionally appeared ever since the revival of trade at the beginning of the Middle Ages, but their number increased rapidly with the growth of the power of the mercantile classes. There were enough of them in several countries in the first half of the seventeenth century to form considerable groups of men of ability. These men were brought together by their common interests and at first unconsciously formed themselves into clubs and societies. The English group became the parent of the Royal Society of London.

As this society was not consciously invented by an individual, and came into existence through the impulse of prior impersonal social forces, its origin cannot be defined precisely. The original members of the Royal Society, which was approved by Charles II in 1660 and granted a royal charter by him in 1662, gradually became conscious in the forties of the seven-

teenth century that they were forming a definite group. The mathematician John Wallis has described how he joined in conversations in London in 1645 on the new experimental philosophy.

A group of persons met weekly for the performance and discussion of experiments. These were made in the lodgings of one of their members, or in a tavern, or in Gresham College. This institution had been founded on endowments bequeathed by Sir Thomas Gresham in 1575. He was financial adviser to Elizabeth and Cecil, and one of the greatest mercantilists of the age. He founded his college for the instruction of the people of London, believing that the new interests of society, which were mercantilist, had created a need for the general education of the people. Seven professorships, presently held by men such as Wren and Hooke, were established: in divinity, astronomy, music, geometry, law, physics and rhetoric.

Wallis said that the meetings of his friends were first suggested by Theodore Haak, a German resident in London, and that John Wilkins, the brother-in-law of Oliver Cromwell, was prominent in them. Wilkins wrote on mechanics, and was interested in the rationalization of language and the means of communication.

The group tabooed theology and politics, and discussed medicine, anatomy, geometry, astronomy, navigation, statics, magnetism, chemistry, mechanics and general natural phenomena. They met in the optical workshop of one of their members, to have materials and instruments at hand for experiments, or at the lectures of the Gresham professor of astronomy, accompanying him to his lodgings after he had finished his lectures, to continue discussions.

Robert Boyle joined the group in 1646, when he was twenty years old. He wrote to his French tutor that he had been studying "natural philosophy, the mechanics, and husbandry, according to the principles of our new philosophical college, that values no knowledge, but as it hath a tendency to use." He

would be grateful if "good receipts or choice books of any of these subjects" could be sent from abroad, and these would make the sender "extremely welcome to our invisible college."

These meetings began near the end of Charles I's reign, during a period of extreme theological and political tension. To their participants they appeared as a refuge where discussion was restricted to apparently neutral subjects, in which persons of differing theological and political opinions could join without antagonism. The group wished to be unnoticed by the theological and political contestants, and held its meetings in modest obscurity. Perhaps for that reason Boyle described it as the "invisible college." Sprat said that "their first purpose was no more than only the satisfaction of breathing a freer air, and of conversing in quiet one with another, without being ingag'd in the passions and madness of that dismal age."

As the tension in London grew, some members migrated to Oxford. They held similar meetings there, which were fostered by Wilkins, Petty, Willis, Boyle, and others. They met at first in Petty's lodgings, because he lived in the house of an apothecary, whose drugs and apparatus were available for experiments; and then at Boyle's house, because he had constructed a laboratory. Members who remained in London continued to meet until 1658, when their place of meeting was commandeered as a quarter for soldiers.

The meetings were revived at Gresham College after the restoration of the monarchy. The members now sought a more formal organization. They discussed rules for regulating their proceedings and electing new members at their meeting after Wren's lecture on November 28, 1660. Wilkins was chairman, and others present included Boyle, Petty, Wren, Brouncker, and a Scottish nobleman named Moray, who had accompanied Charles during his exile. They compiled a list of forty-one persons suitable for membership, and proposed that members should subscribe one shilling weekly towards expenses. Moray informed Charles of the design for the new society and re-

ported at the next week's meeting that the King "did well approve of it, and would be ready to give encouragement to it." Moray was appointed the first president. During the following year the title of "Royal Society" was apparently suggested by John Evelyn in conversation with Charles. The Society petitioned the King in 1661 for a royal charter, and received it in 1662. Brouncker was the first president of the incorporated society, and the council included Boyle, Petty, Wallis, Wilkins and Wren; and the German scholar Henry Oldenburg was appointed secretary. The members were to be named Fellows. A second and extended charter was granted in 1663, and one hundred and fifteen fellows were elected.

The Society flourished extraordinarily. A history of it was written within five years of its first charter. Abraham Cowley composed a poem on the Society, in which he said that

> None e're but Hercules and you could be
> At five years Age worthy a History.

The history was compiled by Thomas Sprat, later Bishop of Rochester, and published in 1667. Sprat had access to the minutes of the meetings and was supplied with material by other Fellows. His work is a personal interpretation, supported by much cooperative help. Sprat explains the Society as a product of the "inquiring temper of this age." He believes that this arose from the liberty of thought encouraged by the Reformation. He could not carry the origin of the Society many years back, "yet the seeds of it were sown in King Edward the Sixth's, and Queen Elizabeth's reign." Ever since that time, experimental learning had "retained some vital heat," though it had not the opportunities for ripening that it now enjoys. He concludes that the Church of England is the mother of this sort of knowledge, and should therefore give it all nourishment and support.

He explains the objects of the Society, though he feels that "some of Bacon's writing" gives a better account of them than anything he can compose.

He notes that the Greeks exercised their wit and imagination about the works of nature more than was "consistent with a sincere inquiry into them." The Fellows of the Royal Society, on the contrary, avoided the artifices of words, and sought "a bare knowledge of things." Their description required a clear and precise language, so the Fellows aimed at polishing and standardizing English, and using it "to make faithful records of all the works of nature or art."

They wanted to establish a system for perpetually increasing the knowledge of nature. He says that scientists "have the advantage of standing upon" the "shoulders" of their predecessors, and anticipates or inspires a famous remark of Newton's.

The Society was to be international because it was to "found a philosophy of mankind," and not merely of Englishmen's interests. They would "make the Royal Society the general bank, and free port of the world. A policy, which whether it would hold good, in the trade of England, I know not: but sure it will in the philosophy."

Men of all sorts and professions were admitted. When the social status of John Graunt, the celebrated author of the *Observations on the Bills of Mortality* and founder of demology, was mentioned as a bar to membership, the King himself said that "if they found any more such Tradesmen, they should be sure to admit them all, without any more ado." Sprat says that this incident will show the attitude of the Society to the manual arts.

Nevertheless, the majority of the Fellows were gentlemen under no compulsion to work. This had the advantage of preventing too much attention to particular profit and exploitation. Persons who busy themselves too much with the exploitation of a particular process are like the guards who let the prisoner escape and lost the ransom through pausing to pick up some small coin dropped from the prisoner's pocket. "It busies them about possessing some petty prize; while Nature itself, with all its mighty treasures, slips from them." There is

a similarity in this passage and another famous phrase of Newton's, about the undiscovered sea of knowledge.

Their work in laboratories was superior to study in schools, because experimenters cooperate, while students sit and listen. Struggling with experiments teaches modesty, whereas quick memorizing produces slickness and arrogance. Those who take their opinions from others are generally less open to reason than the original discoverers. The free method of enquiry produced greater results than the formal. Sprat suggested that philosophical training was not necessary for experimental work. Indeed, the intelligent amateur could surpass the formal professional, as was shown by the superiority of Cromwell's soldiers.

The knowledge of nature acquired by scientists enabled them to equal and improve upon traditional technique. If they were excluded from surgeries, or from the workshops of mechanics, they would nevertheless, with the help of better instruments, more materials, more hands, and a more rational understanding of medical and manufacturing processes, restore the old processes and discover "many more of far greater importance."

Sprat points out that the settled conditions after the Restoration encouraged manufacture and trade. The Society intended to provide a philosophy suitable for such conditions. It was to be "for the use of cities, and not for the retirements of schools." The Society was "to resemble the cities," which are "compounded of all sorts of men, students, soldiers, shopkeepers, farmers, courtiers and sailors; all mutually assisting each other." The Society had broken down the partition wall, or class barrier, between "all conditions of men" to encourage the study of their techniques and the exchange of their technical knowledge. The Royal Society "goes to the root of all noble inventions, and proposes an infallible course to make England the glory of the western world."

England, as one of those lands that border on the seas, was

"most properly seated" to receive the matter which provides new science. Owing to her situation, she was an exchange for universal knowledge. Her climate and air, "the influence of her heaven," the "composition of the English blood," and the "disposition of her merchants" should, under the leadership of the Royal Society, qualify her for the headship of a philosophical league directing the civilization of Europe.

The Fellows of the Royal Society "escaped the prejudices that used to arise from authority, from inequality of persons, from insinuations of friendship" and other subjective relationships because they were in the habit of attending to things. It was "in vain for any man amongst them" to strive to shine by wit, for the results of their experiments were esteemed, rather than acute comments. As Veblen has since remarked, the attention to things and processes has directed conceptions away from principles of dominance to impersonal relationships.

The work of the Society was a "painful digging and toiling in nature," and less easy and fine than teaching. Consequently, "strict punctilios" of conduct were an encumbrance to them, just as an artificer's best suit is an encumbrance to him when working in his shop. For similar reasons, the Fellows avoid eloquence in the description of their experiments. This quality is "fatal to peace and good manners." They have resolutely rejected all extravagance in expression, all "amplifications, digressions and swellings of style." They aim at a "return to the primitive purity, and shortness, when men delivered so many things, almost in an equal number of words." The Fellows are expected to use "a close, naked, natural way of speaking; positive expressions; clear senses; a native easiness: bringing all things as near the mathematical plainness, as they can: and preferring the language of artizans, countrymen, and merchants, before that of wits, or scholars."

It will be noticed that the influence of science on philosophy and literature was expressed very clearly before Newton and his work were known. The characteristics of thought and writ-

ing at the end of the seventeenth and the beginning of the eighteenth century were not due to Newton's achievements, though they were heightened by them. Newton's modes of thought were rather the efflorescence of a social movement that preceded him.

The new grasp of the nature of experimental science gave Sprat and his contemporaries a better insight into ancient science. He said that Greek physics was utterly useless for the good of mankind. The Greeks regarded physics as an occupation for the private meditations of their wise men. "What help did it ever bring to the vulgar? What visible benefit to any city, or country in the world? Their mechanics, and artificers (for whom the true natural philosophy should be principally intended) were so far from being assisted by those abstruse doctrines; that perhaps scarce any one of those professions, and trades, has well understood Aristotle's *Principles of Bodies*, from his own time down to ours."

This had had unhappy consequences. Whereas arts and manufactures had tended steadily to improve, mental philosophy had been subject to severe vicissitudes. When empires fell, their mental culture dissolved, though their crafts tended to survive. This was owing to the divorce of mental philosophy from the crafts. It was cultivated to a degree which placed it beyond the understanding of those unable to devote the whole of their lives to it, and was therefore incomprehensible to men of business. This led to the belief that it was useless. If it had been kept nearer to material things and processes, it would have survived better, like ploughing and iron-making, through the periods of social turmoil. "By bringing philosophy down again to men's sight, and practice, from whence it was flown away so high: the Royal Society has put it into a condition of standing out, against the invasions of time, or even barbarism itself." By "establishing it on a firmer foundation than the airy notions of men alone," that is, "upon all the works of nature," and "by turning it into one of the arts of life of which men

may see there is daily need, they have provided that it cannot hereafter be extinguished," as in the past, "at the loss of a library, at the overthrowing of a language, or at the death of some few philosophers"; for "men must lose their eyes, and hands, and must leave off desiring to make their lives convenient, or pleasant, before they can be willing to destroy it."

Sprat says that while the Royal Society had been considering methods of improving building materials, and the design of houses, roofs, chimneys, drains, wharves and streets, the disasters of the Plague and Fire of London had occurred. These had provided a motive for redoubling their labour on research into the constitution of nature. Improved technique provided the means for the quickest recovery from these disasters. It was the best source of encouragement, and for this reason it seemed that "the shops of mechanics" provided the best moral besides natural philosophy. Wren, Hooke, and their colleagues had the inspiration of building a new city on the most advantageous site in "all Europe for trade and command." They could plan a new world centre for trade and culture. The Royal Society set out to make a "universal, constant, and impartial survey of the whole creation" as a contribution to that aim. Its international aspects were cultivated by correspondence with the leading scientists in all nations, during peace and war. The King gave special permission for the Society to continue its correspondence with Huyghens during the Anglo-Dutch war.

The mixture of merchants with scholars added an "industrious, punctual and active genius" to the quiet and reserved temper of men of learning. It led to sustained efforts to improve technique. The Society's first endowed lecture was on the subject of mechanics. "The noise of mechanic instruments" was heard in the King's palace at Whitehall. Chemical experiments were conducted there at his command. He increased the privileges of the College of Physicians, and planted a new garden for medicinal herbs. He considered planting fruits and trees and establishing an observatory in St. James' Park. He en-

couraged improvements in the design of ships, sails, keels, etc., and was very ready to "reward those that shall discover the meridian," that is, shall show how to discover longitude at sea. He presently founded the Royal Observatory at Greenwich.

Sprat found the source of the energy which inspired all this activity in the social movements of the Reformation and Civil War. Few experiments had been made in Elizabeth's time because the classics were not yet assimilated, and the Reformation was not yet complete. But the Civil War "stirred up men's minds from long ease and a lazy rest, and made them active, industrious and inquisitive." The relics of antiquity were mastered, and men became weary of religious disputes, and "not only the eyes of men, but their hands" were open and prepared to labour.

The Fellows were asked to make a survey of treatises and descriptions of the natural and artificial products of all countries. They scoured the world for technical knowledge and ideas, like the contemporary planners in the Soviet Union. They started a catalogue of all trades, works and manufactures, noting the processes, instruments, tools, engines and manual operations employed. They started a catalogue of all the natural things, animals, plants and minerals, found in England. They began a survey and map of the stars and planets. They studied "the way of finding the longitude of places by the Moon." They studied methods of improving the manufacture of tapestry and silk. They sought how to improve saffron and the cultivation of potatoes. They attempted to discover how to make "iron with sea-coal," one of the technical processes fundamental for modern industry and the development of England as it relieved the iron smelter from the dependence on wood fuel, in which England was deficient. They attempted to use "the dust of black lead instead of oil in clocks," and forecast the modern use of graphite lubricants. They studied the smelting of lead ore and the use of pit coal. They attempted to change the taste of edible flesh by altering the feed

of the animals from which it was procured. They tried to make wine out of sugar, so that an over-production of sugar in the West Indies might be utilized to replace expensive imported wines.

Hooke outlined a scheme for systematic meteorological observations. Petty designed and built a double-bottomed ship. Brouncker studied the recoil of guns by full-scale experiments in the courtyard of Whitehall. His precise analysis of the phenomena led towards the distinction between energy and momentum. Graunt "deduced many true conclusions, concerning the gravest, and most weighty parts of civil Government, and human nature" from the bills of mortality which had passed through the hands of every tradesman for many years without profit to anyone, "except only to the clerks that collected them." Hooke invented the watch spring. Wren invented a constant temperature furnace, and a thermostat for hatching eggs, and keeping at a constant temperature watches for finding longitude. He also investigated the mechanics of rowing, sailing, swimming and flying, and experimented on the transfusion of the blood. Descartes had based his conceptions of the laws of motion on experiments with tennis and billiard balls. Wren continued experiments with balls, and made the dynamics of collision clear for the first time. He studied the vibrations of pendulums, and conceived an arrangement which would simulate the movements of the solar system. He speculated on the law of gravitation, and his discussions with Hooke and others provided an important background of ideas for Newton's thoughts. Sprat said that Wren could "lay peculiar claim" to the "doctrine of motion, which is the most considerable of all others, for establishing the first principles of philosophy, by geometrical demonstrations." He attempted to improve the use of terrestrial magnetism for navigation, and he invented rotating drums for continuous wind and temperature records.

Wren's talent, like Leonardo da Vinci's, was wonderful, but

its chief significance lies not in its individual fascination as a magnificent flower of human ability, but in its integration of many arts and sciences. The indivisible relationship of all human activities is explicit in a career like his, and the impulse that science owes to practical and social interests is exemplified.

Sprat discusses the influence of the Royal Society's activities on the methods of education. He complains that the classical education unfits a man for business. It follows the "preposterous course" of teaching general rules before particular things, and it makes students "witty in objecting" rather than "ready in resolving, and diligent in performing." The young should be educated through the senses and memory, and not through the intellectual judgment. The best remedy for the defects of literary education is experimental training. All men are equal before the facts of nature, and the scientist "looks on everything standing equal to it, and not as from a higher ground." He does not see the world in terms of personal authority and the conceptions of social rank. The upper classes cannot gain a deeper insight into nature merely by virtue of rank.

The experimenter does not always "handle the very same subjects that are acted on the stage of the world; yet they are such as have a very great resemblance to them." The experimenter receives a training appropriate for practical life, and his experience fits him to live in England rather than "Athens or Sparta." His careful attention to facts and measurements cultivates the prudent habits characteristic habits of the bourgeois. "The course of things goes quietly along" according to the even law of cause and effect, Nature plodding on like a patient and industrious workman. One might also draw the reverse conclusion that bourgeois habits prepare men for work in experimental science, and when a bourgeois society has come into existence it may tend to cultivate experimental science.

Sprat, like Bacon, is at pains to prove that there is no conflict between science and religion. He instances Christ's miracles as divine experiments. In his own time, the piety of tradesmen

has been particularly conspicuous. He points out that the English Church and the Royal Society have the same head, in the person of the king. They are both reformists, for one has reformed religion, while the other has reformed philosophy. "They both follow the great precept of the apostle, of trying all things," and holding fast to that which is good. If the English religion were otherwise, and "an enemy to commerce, intelligence, discovery, navigation, or any sort of mechanics; how could it be fit for the present genius of this Nation?" Providence had indeed exhibited its benevolence by arranging this happy compatibility.

In these circumstances, it was legitimate to expect that the technique of manufacture would be improved. It would in fact be necessary to consider the results of improvements, and foresee whether "they will not ruin those trades that are already settled." He is confident that they will not, by appeal to a labour theory of value. "The hands of men employed are true riches: the saving of those hands by inventions of art, and applying them to other works, will increase those riches." Artisans should therefore not fear unemployment through the introduction of technical inventions.

The Dutch had particularly encouraged the invention of labour-saving devices, and immigration. This explained why they were more prosperous than the English.

The most rapid development of trade and industry would arise from direction by experimental philosophers. They would invent new trades. Modifying Plato, one could forecast that when mechanics had mental training, and philosophers had mechanics' manual skill, philosophy would attain to perfection.

The discovery of new worlds was to be expected from the invention of a reliable method of determining longitude at sea. As the Royal Society was studying this problem with "peculiar care," its solution "cannot now be far off." The microscope had already revealed a far greater number of things than were contained in the universe visible to the naked eye.

Agriculture could be improved by the introduction of new plants. It was probable that the cultivation of flax could be established in Ireland, where many vast tracts of ground were "now only possessed by wild beasts, or Tories almost as wild."

In the past technical inventions had been due mainly to the demands of "luxury, or chance, or necessity." The rate of development in expensive building and clothing had been fast but there had been no improvement in building materials. Nor had there been any improvement in fundamental productive inventions, such as the cart and the plough. This division in direction of improvement reflected the circumstances of the origin of technique. "The riches and dominion, that were at first in common, were unequally divided: the great, the wise, or the strong obtained a principal share; and either persuaded, or constrained all the rest to serve them with their bodies. Thence sprung all the arts of convenience, and pleasure, while the one part of men would not be content to live according to the first plainness of Nature: and the other were compelled to work with their hands, for the ease, and pleasure of their masters' lives, and the support of their own."

The inventions of peace, war, cities, palaces, food, clothing and recreation had sprung from this source, which was "the most natural method of the foundation, and progress of manual arts." They might be improved by the discovery of new materials and processes.

The necessary research could not be undertaken without expenditure. The poets said that moral wisdom thrived best in poverty, but it was certain that natural wisdom did not. It was fortunate that an unusual number of gentlemen in England were prepared to spend money on experiments. This was owing to the protection of the sea. Her trade and forces were on the sea, and manned by working men. This enabled her gentlemen to stay at home and enjoy leisure. They lived in country houses, where there was much opportunity for observing nature. The gentlemen of Continental nations such as France,

Spain, Italy or Germany were shut up in castles or cities, or engaged as officers in the big armies, and had less leisure and opportunity for experimental enquiry.

The English also had the benefit of changed social manners. The former governing classes talked only with their servants and travelled little. The new governing class was more affable, which increased the exchange in ideas. The gentry could no longer be averse from promoting trade through fear of social debasement. "For they are to know that traffic and commerce have given mankind a higher degree than any title of nobility, even that of civility, and humanity itself."

Sprat published his remarkable book four years before Newton's, and eleven years before Halley's, election to the Royal Society. A great scheme for the development of science to the benefit of mankind had been conceived and to a considerable degree put into operation by the Fellows of the Royal Society before those great men joined their ranks. The scope of the plans and the profusion of experiments and achievements show that the development could have been due only to a powerful social movement, and not to the accidental inspiration of a few talented men. The century preceded the genius in the "century of genius." Newton clarified and worked out with unparalleled ability some of the conceptions and methods emerging from the movement that led to the formation of the Royal Society. But the degree of his success had some unfortunate, besides advantageous, effects. It helped to concentrate scientists' attention on particular problems, and to professionalize the Royal Society. The Society's early enthusiasm with planned research for the benefit of mankind, which it had learned from Bacon and the social movement that had inspired him, gradually declined in favour of technical virtuosity. It is probable that the social planning of research, and the conduct of particular researches, could not easily be done together, and that they separated through necessity. The Society's interest in the social utilization of science dwindled, and even the

quality of particular researches, as described in its transactions, declined at the end of the seventeenth century. Hamilton has pointed out that the decrease of the rate of development of science at the end of the seventeenth century is parallel to the first halt of the general rise of prices since the discovery of America. Trade remained very profitable until the end of the century. This provided the optimism, and the motive for the enterprise, of the founders of the Royal Society.

Merton has made a very interesting and able analysis of the correlation of the development of science in the seventeenth century with industrial development, and especially with the growth of Puritanism. He has demonstrated in detail the inseparable development of science, technology and religion in this period, and has shown that the general themes of science were set by the sociological conditions, while interest in particular subjects within these themes varied according to the success and ability of talented individuals. For instance, Boyle, Hooke, Newton, Huyghens, Wren and Halley produced a special interest in physics by their remarkable achievements, but even they did not produce more than an extra expansion of a vigorous, pre-existing development.

In 1667 the Royal Society was only five years old. In 1940 it is 278 years old. Its long career has been packed with fascinating scientific events, but its record has never been more brilliant than in its first thirty years. The best features in the surviving Society had already been formed in that time; but some of the most important original features have withered for two centuries. The insight into the social relations of science shown by Bacon and the founders had virtually been forgotten until recently. The revival of this insight is connected with contemporary social changes, which rival or surpass the great social changes that occurred in England in the seventeenth century. The Royal Society's relative lack of interest in the social relations of science since the end of that century

until today is a reflection of an unchanging conception of the relation of science to society in the intervening period.

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THE GREAT PROBLEM OF THE SHIPPING PERIOD

Andrew Mackay wrote in his treatise on longitude, published in 1810, that "in every commercial state, any work that has for its object the improvement of the art of navigation will always be favourably received." The growth of ocean trade provided a powerful motive for improving the science of navigation. This depends on the determination of position on the surface of the ocean. If land is in sight, and landmarks are recognizable, the position of the ship may be determined by consulting a chart of the place observed, but if the ship is on the open sea, this method cannot be used. Position is given most conveniently in terms of latitude and longitude, so the ocean navigator requires methods of determining these when out of sight of land. As he is on a rolling and pitching ship, which sails through climates of varying temperature and pressure, he needs methods that will give accurate results in spite of these disturbances. Latitude is fairly easily determined from the altitude of the sun and stars. During the Middle Ages this was done with the elementary astronomical instrument, the cross staff. Its use was superseded by the sextant. This was introduced by Hadley in 1731, and was independently invented by Newton in England and Godfrey in America. Hooke preceded these with the invention of a similar instrument. Thus the sextant was independently invented almost simultaneously in different parts of the world by several persons. Its essential feature consists of mirrors which enable the observer to bring the images of two observed stars to coincidence, and thus ac-

curately measure the angle between the stars. It is equally useful for finding the angle between the sun's lower limb and the apparent horizon. It gives a direct and quick result, which is accurate even when the instrument is held in the hand.

The problem of determining longitude was far more difficult. The direct way was by dead reckoning. The speed of the ship was estimated, or measured, by casting a log overboard at the prow of the ship and noting the time the ship (whose length was known) took to sail past it. The distance travelled east or west could then be computed, and this would give the longitude. When Columbus sailed back to Europe from the discovery of the New World, he disputed with his lieutenant whether they were approaching Madeira or the Azores. Each was skilled in the known methods of navigation, but their estimates of longitude differed by six hundred miles. In fact, neither knew where they were. Columbus had inspired his crew by falsely persuading them that he could accurately determine the ship's position. His calculation of longitude was so erroneous that he believed that Cuba was part of Asia, and forced his crew to sign an affidavit to that effect. As Gould remarks, he attempted to abolish the Pacific Ocean by legislation.

The inability to determine longitudes led to very serious losses at sea. Between 1691 and 1721, England alone lost five naval squadrons from this cause.

When a ship sails along a parallel of latitude, the heavenly bodies preserve a constant altitude but cross the meridian, and rise or set, earlier or later, to an observer on the ship. The longitude of the ship may be determined from the difference between local time on the ship and standard time on some fixed meridian of reference, such as that which passes through Greenwich.

The first theoretically satisfactory method of determining local time was proposed by Galileo. The eclipses of Jupiter's satellites, which occur frequently and at very approximately

the same time for observers at all points on the earth, may be predicted. Longitude may therefore be determined by comparing the time of an eclipse on a known longitude with the local time of the eclipse as observed on the ship. The method proved to be impracticable because the eclipses could not be steadily observed if the ship had the slightest movement, and for other technical reasons.

The most promising method of determining local time from the heavenly bodies is provided by the moon. It moves relatively rapidly across the sky, covering about twelve degrees in twenty-four hours. This gives changes of position large enough for accurate measurement. Hence, if the position of the moon could be accurately predicted, its place relative to the stars would give local time. Great efforts were made to collect accurate observations of the moon's motion. The Greenwich Observatory was founded in 1675 chiefly for this purpose. Flamsteed was instructed by Charles II, when appointed the first Astronomer Royal, "to apply himself with the utmost care and diligence to the rectifying the tables of the motions of the heavens, and the places of the fixed stars, in order to find out the so much desired longitude at sea, for perfecting the art of navigation."

The production of a theory of the moon's motion based on the new observations required the discovery of a general theory of planetary motions. This was given by Isaac Newton twelve years after the founding of the Greenwich Observatory, in his theory of universal gravitation. He said that this was the most difficult problem he had ever attacked, and was the only one that gave him headaches. The moon is attracted by the sun and planets, besides the earth, so its motion is extremely complicated.

The method of determining longitude from the moon's motion was suggested by Werner in 1514, but even Newton, two centuries later, had not perfected it beyond an error of two or three degrees, or from one to two hundred miles.

Another method, proposed by the Flemish astronomer Frisius in 1530, was the use of a very accurate watch. Portable clocks driven by coiled springs had been invented some thirty years before. Slow progress was made with this suggestion, owing to the difficulty of making accurate watches. The Nürnberg "eggs," or watches, varied about a quarter of an hour a day, while a variation of less than two or three seconds was necessary for satisfactory determinations of longitude. Huyghens was the first to construct a timekeeper designed to give longitude at sea. This clock, which was made in 1660, was regulated by a pendulum, to provide more exact running. In order to perfect his clock, Huyghens analysed the mathematical theory of the pendulum, and discussed the influence of the rotation of the earth, and the shape of the earth, on its motion. This analysis, which contains the first correct theory of circular and wave motions, was published in 1673, and greatly assisted Newton in his creation of the general theory of planetary motions. If the period of the pendulum varied at different places on the earth's surface, it could not be of assistance in determining longitude. Hence experimental and theoretical knowledge of the pendulum, and its related problems of variation of gravity, of the shape of the earth, and the theory of circular motion, became of the first importance in connection with the possible determination of longitude. An expedition was sent in 1660 by the French Academy of Sciences to measure the period at Cayenne, in South America, of a pendulum that beat seconds at Paris. It was found to be slower. In 1672 Richer observed that a Paris seconds pendulum lost two minutes twenty-eight seconds daily at Cayenne. Newton deduced from this that the earth bulges at the equator, and is a spheroid whose diameters are as 230:229. The King of France ordered a direct measurement of the shape of the earth by survey. Expeditions were sent to Peru and Swedish Lapland about 1735, and returned with figures that confirmed Newton's prediction.

The *Principia* may be regarded, to a large extent, as a theo-

retical synthesis of the problems set in gravity, circular motion, planetary and lunar movement, and the shape and size of the earth by the demand for better navigation. But it did not provide satisfactory practical answers. Newton said in 1713 that lunar theory would not then reliably give position within two or three degrees, or one to two hundred miles. "A watch to keep time exactly" would do, "but, by reason of the motion of a ship, the variation of heat and cold, wet and dry, and the difference in gravity in different latitudes, such a watch hath not yet been made."

The British Government established in 1712 a Committee on Longitude. A bill was passed offering a reward of up to £20,000 for "such person or persons as shall discover the Longitude," and sanctioning expenditure on encouragement and experiment. The Commission on Longitude lasted until 1828, and in 115 years considered a number of practical proposals and innumerable suggestions from cranks. Swift satirized these in his "Ode for Music, on the Longitude." It expended altogether about £101,000 on aids and rewards to discoverers of longitude. Prizes were also offered by other governments. Philip II of Spain offered the first in 1598, perhaps through memories of the navigational disasters to his Armada.

The competitors for the English prizes concentrated on the lunar theory or on the construction of accurate watches. The astronomer Halley studied tables of lunar observations and discovered a periodicity of eighteen years eleven days in the lunar motion. This enabled him to determine the moon's motion within two minutes.

Lunar theory was gradually improved, and Mayer in 1755 produced tables which gave a result correct to within half a degree. He died in 1762, and his widow was awarded a prize of £3,000 by the Commission of Longitude. The mathematician Euler received £300 for discovering the improved theory upon which Mayer's computations were based. The tables were tested on voyages to St. Helena and the West Indies.

Mayer's tables were published in 1766 by the Commissioners, as the first issue of the *Nautical Almanac*, which has appeared annually ever since.

While the astronomers were struggling with the lunar theory, clockmakers attempted to construct watches unaffected by motion, temperature, humidity and gravity, which would keep time accurately enough to give the longitude within half a degree. The problem was first solved in 1764 by John Harrison, the Yorkshire carpenter, after forty years of experiment and construction. He spent six years on his first machine, which was completed in 1735 and weighed 72 lb. It was tested on a voyage to Lisbon and gave a promising performance. He was awarded £500 to construct a second machine. This was completed in 1739 and weighed 103 lb. He received a further £500 for a third machine, and seventeen years passed before it was finished in 1757. It weighed 66 lb. He now proposed to construct a timekeeper like a large watch. This fourth machine, which he named a chronometer, was about five inches in diameter, and beautifully finished. It was not supported on gimbals to keep it horizontal in the ship, but was merely laid on a cushion in a case.

It was tested on a voyage to Jamaica in 1761, and gave the longitude correct to less than two minutes of a degree. Harrison was entitled to the prize if he could prove that the performance was not accidental. This was difficult, and a long wrangle commenced. The contemporary Astronomer Royal, Maskelyne, was biassed in favour of the lunar theory method, and had advised the acceptance of Mayer's tables. A second test of Harrison's chronometer showed that it would measure time correct to fifteen seconds in five months. He was now doubly entitled to the prize, but the Commissioners would not give it to him until he had shown them the works, which was not part of the original offer. But he received the balance of the first half of the £20,000 in 1765, when he was seventy-two years old. He had to make two more chronometers to

prove that they could be repeated. The Board still procrastinated, and proposed very severe tests for them. Harrison was now seventy-seven, and still had not received the second £10,000. But George III became personally interested in the machines. The tests on one of them were made at the King's private observatory at Kew, and George took a sporting interest in the performance. He attended the daily observations, and was keenly interested to see how they kept inside the records. He finally used his influence to force Parliament to give Harrison the remaining half of the prize. This was achieved in 1772, when Harrison was seventy-nine.

He had proved by patience and fine workmanship that successful chronometers could be made. His machines were soon superseded by those of Le Roy, who had a more brilliant conception of the principles of chronometer design, and could think out problems that Harrison solved empirically. The problem of the industrial production of chronometers at reasonable prices was solved by the end of the eighteenth century.

The chronometer remained the standard instrument for determining longitude at sea until the twentieth century. It was then superseded by the almost miraculous radio time-signal that gives standard time virtually instantaneously at every point on the earth's surface.

The lunar theory became the chief scientific problem of the eighteenth century. It received intense intellectual study. The late Astronomer Royal, F. W. Dyson, has written that up "to the present day, distinguished mathematicians of England, France, Germany and America have given large portions of their lives to the Lunar Theory. More arithmetic and algebra have been devoted to it than to any other question of astronomy or mathematical physics."

This attention is not due to a peculiar curiosity of scientists in the moon, but to the former importance of lunar theory for navigation. In the seventeenth and eighteenth centuries, when

English society was based on ocean trade and navigation, astronomy, which through lunar theory was the science most closely connected with navigation, became the senior science in universities. Its prestige was not surpassed by that of other branches of physics until the middle of the nineteenth century, when heat and electricity became the leading physical sciences. The amount of arithmetic and algebra devoted to the theory of electricity must be approaching, or already have surpassed, that devoted to lunar theory. This is not because scientists now find electricity more curious than the moon, but because electricity is of more interest than lunar motion to a society in which the problems of industrial production have become more important than those of ocean trade.

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THE NEW SLAVE

Trade and manufacture necessarily grow together and exert a mutual influence, but in some periods trade has the chief initiative, and in others manufacture. Trade possessed the chief initiative in the fifteenth to the seventeenth centuries. The feature of this period was the expansion of trade, which stimulated the production of raw materials and finished goods. Ancient technical methods of agriculture, mining and handicraft were strained to the limits of their possibilities in the effort to supply the new demand. The water wheel and the windmill were improved, and increased in size until they became unwieldy and liable to excessive breakdowns for repairs. But these machines could not meet the increasing demand for mechanical labour. The number of convenient sites possessing water-power was limited, and the wind was fickle and weak. Some producers deserted this line of development, which had been followed steadily since the end of the Dark Ages, and turned back to slavery for an increased supply of power. The growth of negro slavery in the West Indies and the southern English colonies in North America provided the most striking example, but there were many others. Slavery was revived in Europe in the eighteenth century by the landowners of Eastern Prussia. Pirenne has commented on the great influence of this event on modern European history. It affected the tradition of these landowners, who provided a large number of the officers of the German army and civil service. When Germany became a modern industrial nation in the second half of the nineteenth century, she inherited this

governing class, with its dictatorial tradition. Her foreign policy, which was an important contributory cause of the war of 1914, was formed by this class. The same class helped to restore authoritarian government after the war by assisting Hitler to seize political power.

The social conditions in the eighteenth century were not, in general, favourable to a return to slavery. The improvement of machinery seemed to offer a quicker route to increased profits. At that time machines were generally small, and evidently subordinate aids to the workman. The best way of improving the machine was to encourage the workman who was its master. Far-sighted social thinkers advocated initiative for the workman as the best way of improving machinery and increasing production. This tendency, combined with centuries of Christian agitation for respect for the individual, made a general return to slavery unprofitable. Invention became the most promising source of increased production.

The industrial growth that followed the period of the great navigations is exemplified in the British coal industry. London became a great port, with a rising number of East India traders, and industries connected with them. The supply of English wood for domestic fires, industry and shipbuilding was insufficient, and substitutes were required. The situation was reflected in the increase in the price of firewood. While general prices rose by a factor of three from the middle of the fifteenth to the middle of the seventeenth centuries, the price of firewood rose by a factor of eight.

The new demand for fuel was met by increasing the imports of coal from Newcastle. This emancipated London from dependence on the naturally meagre English wood supply, and allowed its population and industry to rise to a new degree of concentration.

The effect of this development on the production of coal in the Newcastle district is seen in the figures compiled by Nef and quoted by Merton. The annual export to the London

district rose from 22,000 tons about 1550 to 690,000 tons about 1680, an increase of thirty times. The total annual output rose from 65,000 tons to 1,225,000 tons in the same period. The annual output of the whole British industry rose from 210,000 tons to 2,982,000 tons.

This prodigious rise of coal production was not an exceptional industrial phenomenon. The output of the salt and glass industries increased about fifteenfold. There were comparable advances in the alum and copperas, saltpetre, soap and brewing industries. A great industrial revolution occurred in the century preceding the *Principia*. It was followed by a century of slower progression. The annual output of coal rose from 2,982,000 tons about 1680 to 10,295,000 tons about 1780, or only threefold in comparison with the fourteenfold of the previous century. In contrast, the output rose to 241,910,000 tons about 1900, so that during the nineteenth century the increase was about twenty-fourfold. The rate of scientific discovery shows a parallel variation. It was very rapid until the end of the seventeenth century, then relatively slow until the end of the eighteenth century, rising again during the nineteenth century. The growth of science in the seventeenth century was associated with an industrial revolution little less great than that which occurred at the end of the eighteenth century.

The increase of coal production between 1550 and 1680 involved a qualitative besides a quantitative change in the industry. Hitherto it had been a local hand industry in which men picked a few tons of coal from outcrops in hills or on the sea shore. Now it had become a national industry in which large quantities of material were transported over great distances. It provided conditions for the growth of capitalistic organization and the invention of mining machinery that would increase production.

The preoccupation of inventors with mining problems at this time is reflected in the patents issued. Nef states that

seventy-five per cent of the 317 patents issued in England between 1561 and 1688 were directly or indirectly connected with mining. Forty-three of these were devices for improving the drainage of mines. Twenty per cent of all the patents issued between 1620 and 1640 dealt with water-raising and drainage. The problems that Agricola had discussed so well in the middle of the sixteenth century in connection with metal mining became more acute than ever through the rapidly increasing demand for coal and ores. The exhaustion of outcrops made the drainage of deep mines the most pressing technical problem. The ancient types of vacuum and force pump could no longer provide adequate service. Other ways of raising water were sought. Inventors tried to find new methods of blowing water up pipes. Heron of Alexandria had employed the expansive force of heated air for driving water through fountains. The inventors of the Renaissance tried to use steam for the same purpose. They did not clearly distinguish between hot air and steam. Leonardo da Vinci had investigated the pressure produced by steam, and the Italian della Porta, who followed in his tradition, published in 1606 the first description of a machine for raising water by steam pressure. The water to be raised was held in a tank with a rising pipe, and was forced up the pipe by admitting steam to the tank from a boiler.

Another source of propulsion was gunpowder. Accurate knowledge of the properties of gunpowder was one of the chief interests of the military monarchs who founded the Royal Society and the French Academy of Sciences. When Huyghens was engaged by the latter body at its foundation in 1666, he directed researches on the possibility of using gunpowder as a motive for an internal-combustion engine. He engaged Denis Papin to assist in this work. Papin found that he could not make the gunpowder engine work because "a fifth part of the air" remained in the cylinder after each explosion, and prevented the formation of a perfect vacuum. He sought a working substance that left no residue, and reflected that this

could be obtained from steam, which may be completely condensed into water and in this form conveniently removed from the working cylinder, leaving a perfect vacuum. Papin embodied this idea in a machine. He constructed a vertical cylinder with a piston, and with heat applied to the base of the cylinder. The water turned into steam and forced the piston up, where it was held by a catch. The machine was allowed to cool, so that a vacuum was formed under the piston. When the catch was released, the piston was forced down by the pressure of the atmosphere and could be used to do work. Papin published a description of this machine, which is the essential part of the steam vacuum engine, in 1690. While he had been advancing towards the piston engine, Thomas Savery, a native of Devonshire, employed della Porta's method of raising water by direct steam pressure in a practicable machine. He was awarded a patent in 1698 for a "new invention for raising of water and occasioning motion to all sorts of mill work by the impellent force of fire, which will be of great use and advantage for draining mines, serving towns with water, and for the working of all sorts of mills where they have not the benefit of water nor constant winds." He wrote a tract entitled *The Miner's Friend*, in which he showed how his engine could be used to drain mines. It seems that he conceived that his water-raising engine would be used to keep water mill-wheels running in dry weather by pumping the water back from the tail race. Savery may have received hints for his invention from the work of the Marquis of Worcester, who left obscure accounts of engines in his *Century of Inventions*. According to a work published in France in 1664, the Marquis made a machine which would raise four large buckets of water forty feet in one minute.

Savery demonstrated his machine to the King and the Royal Society in 1699. It consisted essentially of a tank connected by a pipe with a water sump. Steam was admitted to the tank, and then condensed. The vacuum so formed caused the water

to be pushed up through a non-return valve from the sump into the tank. Fresh steam was now let into the tank, and the pressure forced the water through a vertical delivery pipe.

Savery was able to make one-horse-power pumps, which would raise water about fifty feet, for about £50. His larger pumps were unsuccessful, owing to the engineering difficulties of making good pressure tanks and joints. When these became surmountable by improved engineering technique, his principle was employed successfully, and was embodied in the pulsometer pump introduced in 1876, and is still used.

Savery apparently dropped his inventions as soon as he was appointed to a sinecure in 1705.

Another Devonshire man, Thomas Newcomen, was also working on the invention of steam pumps. He was an ironmonger in Dartmouth, and supplied iron tools to the Devonshire tin mines. During his business visits to the mines, he noticed the heavy cost of the horse-driven drainage pumps, and sought to invent a fire-driven pump to replace them. Newcomen was at work on this engine in 1698, before he had heard of Savery, and he experimented for ten years before he had solved his problem. This was mechanical, and consisted of making the operation of a Papin's cylinder self-acting. The history of his procedure is quite unknown. There is no evidence that he had read any account of Papin's works, and the story that he had been advised by Robert Hooke is discredited.

He had to make several first-rate inventions in the course of his achievement. He invented valve-gear, which, apart from the watch, was the first self-acting mechanism. He introduced the internal spray for cooling the steam inside the cylinder with the maximum speed, and the important snifting valve which released the obstructive dissolved air driven out of the boiler water by the heating.

He presently found that he could not patent his engine, because Savery's patent covered all engines deriving their patent from fire, so he went into partnership with Savery. They built

a machine near Dudley Castle in 1712 for draining a mine in the Staffordshire coalfield. This was the true occasion of the birth of the steam engine. A description of the machine mentions no less than fifty-six parts. It raised water 153 feet at a rate of 120 gallons a minute.

Newcomen engines were in use in seven English counties by 1715. The first engine used abroad was erected in 1722 at Chemnitz, the centre of the mining industry described by Agricola. As early as 1725, an engine costing more than £1,000 was built in Scotland. The chief item of expense was the working cylinder. This was cast in brass, and cost about £250.

The increasing demand for metal goods had stimulated research on processes for cheapening the production of iron. The ancient method of smelting used charcoal, but the supply of this, especially in England, was inadequate and expensive. Repeated attempts were made to use coal, but were industrially unsuccessful until 1713, when Abraham Darby mastered the technique of smelting with coke made from coal. Whereas the pig iron made from charcoal had been converted into wrought iron, the pig iron made with coke was cast into vessels and pipes. The cost of cylinders for Newcomen engines fell from £250 to £25 when they could be cast in iron instead of brass.

The technical difficulties of iron founding are considerable. Cast iron varies greatly according to composition and preparation. Its properties and the general processes of the steel industry were studied scientifically by Réaumur, who began a series of researches on these subjects in 1711. He published the trade secrets of the steel industry, which were two thousand years old. He identified the various sorts of cast iron by the microscope, and classified them into ten grades. He knew that grey iron was the best for casting, and that it tended to become white and brittle when reheated. He devised tests for strength and hardness, and in general founded modern scientific metallurgy.

Réaumur was acquainted with coke iron smelting independently of Darby, but in spite of this and his great scientific contribution to metallurgy, the French iron industry was unable to utilize his achievements. The economic pressure for the development of the iron industry was greater in England, and technical development followed the pressure of economics rather than the guidance of a scientist in advance of his economic environment. The history of Réaumur's metallurgical work shows how pure science tends to wither unless it is in robust connection with social needs.

The Newcomen engine saved the Newcastle coal industry. Disastrous flooding had started at the end of the seventeenth century, and without powerful new pumps many mines would have been permanently drowned out. The engine was a success in the mining industry, though very inefficient, because it could be fired with low-grade unsaleable pit-head coal. It was less successful in metal mining districts such as Cornwall, where coal was imported and expensive.

No great improvement on the Newcomen engine was made for fifty years. The decline in engineering invention accompanied the general decline in the rate of technical progress in the first half of the eighteenth century, which has already been mentioned. It seems that the Newcomen engine, like the *Principia,* belongs to the seventeenth century burst of technical development. When that burst was exhausted, no great innovation in engines occurred until a new social growth demanded it. The new industrial development started in the middle of the eighteenth century, and was associated particularly with the textile industry. By 1765 an improved engine was overdue. In that year James Watt invented his engine with a separate condenser, and at one stroke reduced engine fuel bills by about 75 per cent.

Watt was an instrument maker attached to Glasgow College, or University. He was asked to repair a defective model of a Newcomen engine used in demonstrations to the students of

natural philosophy. He experimented with it and made it work, and was struck by its very large consumption of steam. He found that the volume of steam used in each stroke was several times that of the cylinder, and he saw that this was caused by the alternate heating and cooling of the cylinder during each stroke. This led him to an experimental study of the properties of steam. He found that steam is about 1,800 times as bulky as water at the boiling point. When the temperature was raised above the boiling point, its pressure rose in a geometrical ratio. If steam was passed into cold water, the volume of the water increased by one-sixth before it began to boil. This meant that the heat in a pound of steam was able to raise the temperature of six pounds of water to the boiling point. He was puzzled by this phenomenon, which was explained to him by James Black, the professor of chemistry in the college, who had just discovered latent heat. Seeing that one cause of the high consumption of steam, and hence of fuel, in Newcomen engines was due to the alternate heating and cooling of the cylinder during each stroke, he thought intensely of how it might be evaded. The solution shot into his mind during a Sunday walk on Glasgow Green. "As steam was an elastic body it would rush into a vacuum, and if a communication was made between the cylinder and an exhausted vessel, it would rush into it and might be there condensed, without cooling the cylinder."

He designed an engine with the working cylinder enclosed in a steam casing connected with the boiler. This kept the working cylinder steadily at the temperature of the boiler steam. The top of the piston, instead of being exposed to the atmosphere, as in the Newcomen engine, was exposed to steam from the boiler through a separate valve. The bottom of the piston, and the empty cylinder below it, were connected to the external condenser, and were therefore in connection with a vacuum. Owing to the difference in pressure between the boiler steam and the vacuum, the top side of the piston was pushed down the cylinder by the steam. Watt had, as it were,

substituted steam for the atmosphere in a Newcomen engine, and now the steam pressure instead of the air pressure did the work.

As the working steam in the Watt engine was at first a substitute for the atmosphere, steam at very little more than atmospheric pressure was used. This reduced the difficulties of boiler design and made the engine safe. Watt subsequently obtained an increase of efficiency by cutting off the steam supply to the piston early in the stroke, so that the steam could do further work by its own expansion. But he obstructed the development of the high-pressure steam engine with or without condensers.

The industrial exploitation of Watt's improved engine was undertaken by the magnate Matthew Boulton. This manufacturer had a large works at Birmingham in which factory and mass-production methods were being evolved. Handicraftsmen were leaving their home workshops to be organized in factories. These conditions stimulated subdivision of labour and demands for concentrated supplies of power for driving assemblies of machinery. Boulton was keenly aware of the increasing demand for mill engines, and reported in 1781 that "the people in London, Manchester and Birmingham are *steam mill mad*." He formed the grand conception of patenting the Watt engine in all countries, and drawing tribute from the industry of the whole world. He had the capitalist idea of conquering the world by industrial instead of military power.

Boulton and Watt drew their patent royalties in the form of a percentage of the saving of fuel through the efficiency of their engine. This led to careful measurement by Watt of the work done by engines. He measured the average work done by horses and fixed a unit of horse-power, and gave the performance of his engines in terms of this unit. As a part of this scientific rating of the performance of his engines, Watt invented the indicator for registering the changes in steam pressure inside the cylinder during the stroke. The indicator con-

sisted of a small piston pressed by the steam from the cylinder against a spring. The amount of compression was recorded by a pointer, which consequently gave the variations of pressure in the working cylinder. In 1796, Watt's colleague, James Southern, arranged that the pointer should carry a pencil bearing on a board connected with the main piston. As this moved backwards and forwards, and the pointer moved upwards and downwards according to the variations in steam pressure inside the cylinder, the pencil traced out on the board a closed curve which gave a complete history of the pressure changes inside the cylinder, and provided the data from which the work done in the cylinder by the steam could be calculated. This is the famous indicator diagram.

The Boulton & Watt firm kept the indicator as secret as possible, and it was not generally known until travellers brought back in 1826 a specimen used by the firm's men in Russia.

The young French physicist, Sadi Carnot, either learned of the existence of the indicator diagram or rediscovered it. He set out to discover from a theoretical analysis of the diagram the maximum quantity of power that could be obtained in a Watt engine from the production of a defined quantity of heat in the boiler. Carnot assumed that heat was a fluid and did work in the heat-engine by falling from a high to a low temperature, by analogy with the water wheel. Together with this partly erroneous analogy, he had noted that the transmission of heat from a hot to a cold body through the medium of an engine led to the production of work, while the flow of heat from the hot to the cold part of a conductor did no work, so he concluded that the work done by the engine must have been derived from the changes in volume or state produced by the heat in the water. Hence the power was produced by the repeated addition to, and subtraction of heat from, the water, and was due to a cycle of operations. He then pointed out that the de-

gree of reversibility was one of the conditions that determined the efficiency of a heat engine.

The greater the losses by conduction of heat, friction and leakage during the working stroke, the less is the approach to reversibility, and the less the efficiency. The other factor governing the efficiency was the difference in temperature between the boiler and the condenser. Carnot remarked that his assumption that the amount of heat in the steam was the same at the beginning and the end of the stroke was not entirely satisfactory. He subsequently discovered the error in this assumption, and saw that work arose not from the fall, but from the consumption of heat. From this he calculated the mechanical equivalent of heat, but he died prematurely in 1832 of cholera, at the age of thirty-six, and his calculations were not published until 1878.

A clear understanding of the relation between heat and work was not gained until 150 years after the invention of the steam engine in 1712. This was due to the very low efficiency of the early engines. So little of the heat put into them was used that observers thought that heat was the medium through which the work was done, and not its source. The exact measurement of the consumption of heat in a steam engine is difficult, and was not satisfactorily accomplished until the 1860's, twenty years after the equivalence of heat and work had been proved by other methods.

The introduction of the steam locomotive gave a further impulse to the study of heat. Osborne Reynolds has remarked that the Newcomen and Watt condensing engine "contributed to the discovery of the mechanical origin of heat, in that it led to the recognition of work as the measure of mechanical action; and to the locomotive must be attributed the birth of that philosophical interest respecting heat and work which immediately followed its general introduction. The condensing engine had not been obtrusive—it was not generally seen unless

looked for. The locomotive is obtrusive; it will be seen: and by 1842 locomotives had obtruded themselves pretty well all over Europe. They immediately took their places as objects of as much wonder and interest to the grown people who saw them for the first time as they are still to the young; demanding the attention even of philosophers who had previously studied nothing lower than the planets."

The introduction into physics of the engineer's method of measuring work was made by J. P. Joule, the son of a Manchester brewer. Joule's father had had his son instructed in chemistry by John Dalton, to prepare him for the family business. Joule acquired a knowledge of pumps and engines while playing as a youth among the machinery of the brewery. His precise investigations into the relation between heat and work did not, however, arise directly out of an interest in the steam engine. A new motive power had been discovered. This was the electric current. Volta had discovered in 1800 how to produce an electric current. In 1821 Faraday showed how mutual rotation could be obtained from a magnet and a conductor. Sturgeon invented the electro-magnet in 1825, and the commutator in 1836. In the latter year, when he was eighteen years old, Joule began to investigate the possibility of making electric motors to supersede the steam engine. He started with the erroneous belief that the strength of an electro-magnet might be increased indefinitely, and he was unaware of the electrical effect of induced resistance, which prevents the electric motor from becoming a perpetual-motion machine.

Joule could not make a balance-sheet of the performance of his improved motors without accurate measurements of the heat produced in them while running. The analysis of his results suggested that heat, work, electricity and chemical affinity were equivalent; and he derived the figure of 838 for the mechanical equivalent of heat. He deduced from his results that the Watt engine, in spite of its low absolute efficiency, would never be superseded by the "electro-magnetic engine,

worked by the voltaic batteries at present used," because the work obtained from one pound of coal in a Watt engine was about equal to the work obtained from one pound of zinc consumed in batteries supplying an electric motor, and zinc was much more expensive than coal.

According to Reynolds, Joule's use of the engineer's method of measuring the work done by his electric motors, by measuring how much weight they would lift in a given time, was the first example in physics of measurement in absolute units. His introduction of the engineer's method led to the conclusive proof of the conservation of energy, the chief result of physical research in the nineteenth century. Maxwell subsequently used the ideas of the market to describe this discovery, and compared the material universe with "a system of credit." The growth of the ideas of commercial exchange accustomed the mind to the modes of thought which enabled it later to recognize the existence of the conservation of energy.

The discovery of the conservation of energy is connected with the notion of exchange value. Capitalism cannot be operated without an exact knowledge of the equivalence of different forms of energy. This is needed for accurate fixing of the price of coal, electricity, gas and labour. When these are to be sold in exchange, they must be measured, and a common currency found for them. This currency is energy.

When Joule found that heat was equivalent to mechanical work, he perceived that the heat in a gas was probably due to the motion of its constituent particles. He published a calculation in 1844 showing that if this assumption was correct, there must be an absolute zero of temperature, at about –480° Fahrenheit. He confirmed the assumption experimentally by showing that to a high degree of accuracy "no change of temperature occurs when air is allowed to expand in such a manner as not to develop mechanical power."

Mayer in Germany independently developed the mechanical theory of heat. He started from medical observations on

the human body, which at first sight have nothing to do with steam engines. But, in fact, Mayer made his discoveries through the adoption of Lavoisier's conception of the human body as a heat engine, which had clearly been inspired by the development of the steam engine.

Owing to the erroneous assumption in Carnot's published paper, that no heat is consumed during the working cycle of an engine, theoretical physicists were led to believe that Carnot's cycle and the mechanical equivalence of heat were inconsistent. Clausius was the first to show, in 1850, that this was not so. Kelvin made the same discovery independently, one year later.

The science of heat as a mode of motion, or thermodynamics, was based on two laws: that energy can neither be created nor destroyed, and that on balance of exchange, heat never flows from a cold to a hot body. The new science opened up vast fields of research in two main directions. One was towards a more particular analysis of the properties of gases, and the other was towards the application of the theory of the conservation of energy to general aspects of material nature. Kelvin pointed out that the material universe was moving towards a uniform temperature, and "within a finite period of time to come the earth must again be unfit for the habitation of man as at present constituted, unless operations have been or are to be performed which are impossible under the laws to which the known operations going on at present in the material world are subject." According to Lovering, these conclusions led the *Spectator* to call "heat the communist of the universe," which levels all things. Joule pointed out in 1843 that "we shall be able to represent the whole phenomena of chemistry by exact numerical expressions, so as to be enabled to predict the existence and properties of new compounds."

J. Willard Gibbs made an advance towards this aim. His predecessors, following the guidance of the steam engine, which had actually drawn its own indicator diagram and pre-

sented it to physicists for their consideration, so that the machine directly led the mind, had investigated the relations between pressure, volume and temperature in a single fluid, which was an idealized steam. Their results were of use to engineers but not to chemists, for they work with mixtures of fluids rather than single fluids. Gibbs extended the new science of thermodynamics to mixtures, and thus made it of use to chemists. He started by generalizing the engineer's indicator diagram, and showed that more convenient diagrams describing the thermodynamic properties of systems might be made by using properties other than pressure, volume and temperature. For instance, entropy and volume could be used for describing the thermodynamical condition of mixtures, such as one containing ice, water and water-vapour. He advanced towards Joule's aim, and showed how the formation of new bodies may be forecast in such phenomena as superheating and supercooling. He deduced his celebrated phase rule, which governs the separation of components in mixtures. Roozeboom used it to predict the existence of new substances and interpret the constitution of steel, which is a system of iron and carbon. Freeth provided England with adequate supplies of ammonium salts by its aid in 1914. Without this application of the phase rule, England would have lost the war.

The other line of application of thermodynamics, to the motion of particles, continued an ancient development. Democritus and the Ionian Greeks had invented the atomic theory, but the collection of experimental evidence in its favour began only in modern times. Bacon strongly supported the theory, with his pregnant comments on heat as the motion of particles. Boyle acquired belief in the atomic theory from Bacon, and Newton showed that Boyle's celebrated law connecting pressure and volume of a gas could be deduced mathematically if the gas consisted of particles. Daniel Bernouilli showed in 1738 that the pressure of a gas should be proportional to the square of their velocity. The invention of the steam engine stimulated

these researches into the properties of gases, and the effects of temperature were also considered. In 1816 Herapath obtained a formula suggesting that the product of the pressure and volume of a gas should be equal to one-third of the square of the velocity of its molecules. He erroneously assumed the temperature of the gas was proportional to the velocity of its molecules. Waterston pointed out in 1846 that the velocities of the molecules of a gas are not all equal, owing to their collisions. He correctly assumed that their temperature was proportional to the square of their velocity, and calculated the energy absorbed in their spin. He even discovered that "in mixed media the mean square molecular velocity is inversely proportional to the specific weights of the molecules." The Royal Society rejected his great paper, and placed it in its archives, where it was discovered by Rayleigh in 1892.

Joule calculated in 1848 from Herapath's formula that a molecule of hydrogen at atmospheric pressure and at the freezing point of water would have a velocity of 6,055 feet per second. It was known, however, that molecules did not all travel at the same speed.

When a bottle of ammonia is opened in a room, several seconds elapse before the smell is noticed. The molecules, in spite of their speed, are delayed by collisions with other molecules. Thus the rate of diffusion depends on the distance between molecules, besides their speed. Clausius described this factor as the mean free path. But he assumed the speed of all the molecules was uniform. This could not be true, and the dynamical theory of gases could not progress farther until the actual velocity of any molecule selected at random could be estimated. Clerk Maxwell proposed a method of doing this with the assistance of the mathematical theory of probability. His solution was not entirely sound, but he had incidentally founded the science of statistical mechanics. Since then, the theory of probability has entered ever more deeply into the interpretation of nature. Intimations of the quantum theory of action

appeared in the researches of Boltzmann in 1877, and in 1900 Planck proposed the theory in order to explain the observed mode of radiation of heat and energy from black bodies.

Maxwell had assumed that with a lapse of time a collection of molecules would pass through all possible velocities. This has never been proved, and as C. G. Darwin has explained, some new assumption was necessary for a satisfactory discussion of the problem. This was supplied by Willard Gibbs through his invention of the "canonical ensemble." Instead of trying to deal with the whole variety of molecular motions over a period of time, Gibbs took a series of mental snapshots of the gas. Each configuration of molecules, with their velocities, was independent of the rest, but he chose the snapshots so that there was some convenient relation between them. He then assumed that the properties of the gas would be the same as that of a collection or ensemble of the independent snapshots or configurations. The canonical ensemble is the one which corresponds to all possible motions of the gas which would have the same temperature.

In this process Gibbs seemed to be treating the gas as if it were in several different states at once. Physicists with Newtonian preconceptions did not take to his method, but the principle of uncertainty has now shown that he was profoundly far-sighted. The properties of systems of electrons and nuclei are investigated in modern quantum theory with the aid of the idea of the ensemble. Gibbs went even further with his idea. He described systems with a constant number of atoms as petite ensembles, and regarded them as parts of a grand ensemble into which the total number of atoms is not fixed. This idea has not yet been introduced into physics, but Darwin believes that some of the most difficult unsolved problems will ultimately be solved with its aid.

The study of gases, inspired by the pump and the steam engine, has led the imagination beyond the present frontiers of knowledge. The myriads of flying particles in the cylinder of

engines are the modern slaves who have replaced the crowds of Alexandrian and Roman slaves who performed the hard labour of antiquity, and the study of their behaviour has produced a large part of modern science.

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LUNACY

The rapid increase in the production of coal and raw materials in the seventeenth century was followed by a development of refining and fishing processes. Acids are needed for the treatment of ores and the processes of dyeing, and the demand for them had become urgent early in the eighteenth century. But the price of acids was still very high. Their first preparation had been inspired by the demands of gold refiners and druggists. Expense is not of the first importance to these users, because they are dealing with small quantities of products that may be sold at a high price. Sulphuric acid, which has the widest use in industry, was distilled from vitriol according to the ancient Arabian process, or by condensing the fumes of burning sulphur under an open bell-shaped glass vessel. Lémery, at the end of the seventeenth century, improved the latter process by arranging that it should occur in a closed space. James Ward introduced large glass reaction vessels of sixty-six gallons' capacity, and began the manufacture of the acid on an industrial scale in 1736. He brought its price down from half a crown an ounce to one shilling and sixpence a pound, a reduction of nearly one-thirtieth of its former cost. John Roebuck of Birmingham introduced large leaden reaction chambers in 1746, and reduced the price to sixpence per pound. The British chemical manufacturers created an export trade in the acid and met most of the world demand, besides supplying the needs of home industry. Roebuck sought the aid of the chemist Joseph Black in the invention of a process for making alkalies by decomposing lime with sea-salt. This ultimately proved

unsuccessful, but Black asked James Watt, who had recently invented his separate condenser for the steam engine, to assist him in some of the chemical research connected with it. Roebuck became acquainted with Watt through his work on the alkali process. He had begun to develop coal mines in Scotland, and was in trouble with water, so when he heard of Watt's engine he was immediately interested in it. Watt was indebted to Black for scientific advice and financial assistance, but he needed more financial backing than the professor could provide. Watt's financial debts to Black were taken over by Roebuck, and in return Roebuck shared in Watt's first steam-engine patent. Roebuck was embarrassed in the economic depression of the 1770's, and was unable to give Watt as much aid as he needed. He became bankrupt in 1773, and his share in the patent was secured by Boulton, who had still greater industrial talent.

James Watt was a notable chemist besides being a great engineer. The construction of a practicable machine by empirical methods was not sufficient to satisfy him, and indeed the invention of the separate condenser would have been virtually impossible without using the very new science of heat created by Black. He attempted to analyse the principles of his engine and the properties of the material used in it. This led him to study the physics and chemistry of steam. He investigated the chemical composition of water, and added to the contributions made by Scheele, Priestley and Cavendish to this problem. Watt had great direct influence on British chemical industry. The chlorine bleaching process, proposed by Berthollet, was introduced to Glasgow by him. The difficulty of obtaining solutions of chlorine hindered the adoption of the process, but in 1799 the Glasgow manufacturer Charles Tennant overcame this by his successful development of bleaching powder.

The growth of engineering and chemistry in Birmingham attracted scientists to the city, and gave scope to their gifts. The leading personality among them was Matthew Boulton.

He provided the intelligent hospitality in which they became friends, and formed a group whose intellectual power was far greater than the sum of their individual abilities. After Boulton, the most important founders of this group were the physicians Erasmus Darwin and William Small. The eminence of the former, who invented a theory of evolution and made a speaking machine, besides being the grandfather of Charles Darwin, is well known. William Small was equally eminent, but is less well known. He was a Glasgow doctor who had been professor of natural philosophy for some years in the college of Williamsburg in Virginia. Thomas Jefferson was one of his pupils, and has written in his autobiography that Small "probably fixed the destinies of my life." Small found the climate of Virginia uncongenial, and returned to England. Benjamin Franklin gave him a very earnest introduction to Boulton, and he settled in Birmingham about 1765, with the aim of succeeding to the practice of the chief doctor in the town. Small was a Glasgow man and an old friend of James Watt. When he found that Boulton was concerned with engines, he recommended Watt to his notice. He worked incessantly for six years to form a partnership between them, and accomplished this in 1774. Watt then settled in Birmingham. His patent for the separate condenser was drawn up with the advice of Boulton and Small, though their advice was in fact technically unskilful.

Boulton, Darwin, Small and their friends dined at intervals in each other's houses. They arranged to meet about the date of the full moon, so that the moonlight would help them home. They accordingly named themselves the Lunar Society. One of the members of this society, which was so much concerned with illumination, was William Murdock, the inventor of coal-gas lighting. The other members were James Watt; James Keir, the chemical manufacturer; Dr. William Withering, who established the value of the foxglove, or digitalis, treatment for dropsy used by peasant women; John Baskerville, the famous

type-founder; Thomas Day, the author of *Sandford and Merton* and through this book one of the chief creators of the nineteenth-century ethic of the relationship between the upper and lower classes; R. L. Edgeworth; R. A. Johnson; Samuel Galton, the rich Quaker, and his son; and Dr. Stokes.

Joseph Priestley settled in Birmingham in 1780. His wife was a sister of John Wilkinson, the son of the inventor of the steam-driven blast for iron smelting. John Wilkinson commissioned the first steam engine built by the Boulton & Watt firm, and was the inventor of the machine by which iron cylinders and big guns could be accurately bored. Through this invention, expensive brass cylinders in steam engines could be replaced by much cheaper iron cylinders.

John Wilkinson and his sister, Mrs. Priestley, were grim nonconformists. Mrs. SchimmelPenninck, the daughter of Samuel Galton, records that Mrs. Priestley was her mother's closest friend. She had "unswerving integrity of purpose, such inflexible truth, and such a deep, though stern sense of duty."

Priestley's integrity was as great, but he was more charming. He had a serene countenance and was simple, gentle and kind. Mrs. SchimmelPenninck reported that "he, indeed, seemed present with God by recollection, and with man by cheerfulness." She could remember meetings of the Lunar Society in her father's house when she was a child. Boulton "was tall and of a noble appearance; his temperament was sanguine, with that light mixture of phlegmatic which gives calmness and dignity; his manners were eminently open and cordial; he took the lead in conversations, and with a social heart had a *grandiose* manner like that arising from position, wealth, and habitual command." He "was a man to rule society with dignity." Watts was suited to "the contemplative life of a deeply introverted and patiently observant philosopher. He was one of the most complete specimens of the melancholic temperament. His head was generally bent forward or leaning on his hand in meditation, his shoulders stooping and his chest

falling in; his limbs lank and unmuscular, and his complexion sallow. His intellectual development was magnificent." When Watt entered a room, adults and children thronged round him. He advised everyone on practical problems. He instructed Parisian ladies of fashion on how to cure smoky chimneys and dye clothes, he taught Mrs. SchimmelPenninck "how to make a dulcimer and improve a Jew's harp," and she could remember "a celebrated Swedish artist having been instructed by him that rats' whiskers make the most pliant and elastic painting brush."

She writes: "On one occasion, when the Lunar Meeting, or 'Lunatics' as our butler called them, were seated at dinner, a blazing fire being in the room, we were astonished by hearing a sudden *hissing* noise, and seeing a large and beautiful, yellow and black snake rushing about the room. My dear mother, who saw it was not venomous, said to me, 'Mary Anne, go and catch that snake.' " She succeeded, after some trouble, and the company wondered where it might have come from. Dr. Stokes then remembered that, as he was riding to the house, he had seen it frozen on a bank, and had put it in his pocket, with the intention of dissecting it later. He had forgotten its presence, and it had thawed in the heat of the room and had then escaped.

Joseph Priestley was the son of a cloth dresser, and was born near Leeds in 1733. He studied for the nonconformist ministry, and read science in 1758. Benjamin Franklin encouraged him in 1766 to write a history of electricity. Priestley repeated the experiments described in the literature to see whether he had understood them, and without design found himself making new observations and experiments. He was appointed to a ministry at Leeds in 1767, and his scientific researches flagged, but were revived by a visit from Franklin in 1772. He lived next to a brewery, and investigated the gas evolved by fermentation. He showed that it could be dissolved in water under pressure, and immediately, in 1772, applied his knowledge to the invention of soda water. This attracted much attention. He

improved the pneumatic trough for collecting gases over water, and introduced collection over mercury, which enabled him to deal with gases soluble in water. He discovered nitrous oxide, hydrogen chloride, ammonia, and sulphur dioxide. He handled oxygen and carbon monoxide, though he did not immediately recognize their difference from other gases. He discovered that air vitiated by breathing or combustion may be restored by growing sprigs of mint in it. He deduced from this the grand explanation of why all the fires and animals and putrefaction on the earth did not vitiate the atmosphere. The covering of vegetation continually restored the quality of the air.

Priestley accepted an engagement in 1773 as literary companion to Lord Shelburne. He had comfortable quarters and resources in Shelburne's mansion in Wiltshire. He continued his experimental researches, and while working in Wiltshire discovered oxygen. This was in 1774. Scheele had already made the same discovery, but had not published it.

Priestley breathed the new gas, and recommended its use in medicine. His results stimulated much research on gases and their medicinal effects, which gave Humphry Davy his opportunity, and led to the discovery of anaesthetics.

Priestley grew tired of the Shelburne appointment, and was attracted to Birmingham by the offer of a ministry and the presence of the Lunar Society. Boulton, Darwin and Wedgwood privately paid the expenses of his experimental researches. Priestley subsequently wrote that his "settlement at Birmingham was the happiest event in my life, being highly favourable to every object I had in view, philosophical or theological. In the former respect, I had the convenience of good workmen of every kind and the society of persons eminent for their knowledge of chemistry, particularly Mr. Watt, Mr. Keir, and Dr. Withering."

He showed in 1781 that if a mixture of oxygen and hydrogen

was exploded with electric sparks, dew was deposited. James Watt communicated this result to Cavendish, who continued the research with Priestley's permission, and clearly elucidated the composition of water.

Conversation in the Lunar Society was very free. Candidates were not admitted unless they could discuss the newest and unorthodox ideas calmly. The members corresponded with Berthollet and other French leaders of the new science, and when the social changes of the Revolution began, they followed them with sympathy and excitement. Priestley dropped experimental research, defended the revolution, and answered Burke's attack. He criticized the Church of England, and described it as a fungus and a parasitic plant. He was elected a member for Orne in the French National Convention. James Watt's son, James Watt, Jr., was sent to the National Convention as a delegate from the Constitutional Society of Manchester, and is said to have prevented a duel between Danton and Robespierre while acting as second to Danton.

In 1791, eighty gentlemen of Birmingham celebrated the second anniversary of the fall of the Bastille at a private dinner. A mob was urged to attack them, and the property of everyone known to be sympathetic to the revolution, under the slogan: "No Philosophers–Church and King Forever!" They particularly sought the "Lunatics," and some persons wrote "No Philosophers" on the front of their houses as a protection. Boulton and Watt armed their workmen for defence. The mob wrecked and looted more than one hundred thousand pounds' worth of property, including Priestley's house, with his large collection of historic apparatus and valuable library. Priestley had to flee from Birmingham in disguise, and sailed to America in 1794. There he was subjected to ferocious invective by Cobbett, who had not yet lost hope of advancement by the Tories. Cobbett remarks in his American pamphlet, published in Philadelphia in 1799, that "a desire to defend you,

the People of Birmingham, against the malignant aspersions of Doctor Priestley, was, in some degree, the cause of my first attempting to write."

Priestley had extraordinary energy. He wrote until the pen dropped from his hand, and he spoke and experimented indefatigably. He was very resourceful, and though he did not claim equal skill in theorizing, he could not have taken advantage of chance observations so brilliantly if his understanding had not been guided by good theoretical knowledge. He said of himself that he had "a tolerably good habit of circumspection with regard to *facts;* but as to conclusions from them, I am not apt to be very confident." He and his Lunar Society friends were strong supporters of the phlogiston theory. Partington has commented that though Priestley was heterodox in religion, he was orthodox in science. According to the phlogiston theory, a metal is a compound of a calx, or earthy substance, with a hypothetical entity named phlogiston. When a metal is burned, the phlogiston escapes, and the ash is left behind. This theory is very old and has been traced to Aristotle. It is probably still older, for the departure of phlogiston from a burned metal is analogous to the departure of the spirit from a cremated body. In fact, many chemists regarded phlogiston as the spirit of fire. When a metal is burned, all the spring and life go out of it, and only ash remains. Phlogiston was a relic of animism in chemistry. It provided a logical explanation of many facts, and it could not be disproved without a detailed examination of the changes of weight involved in chemical reactions. This was started by Black, from whom Watt had learned much, but Watt did not carry Black's careful measurement into the details of chemical change, though he revolutionized the conception of mechanical power by careful measurement of the coal consumption of engines and defining the horse-power. Watt and many of his friends were successful business men, with a strain of conservatism besides enterprise. He was conservative in the development of the steam engine.

The phlogiston theory, with its long tradition, probably appealed to this conservative strain in the Birmingham circle. Priestley's chief talent was in manipulation and qualitative research. He had less aptitude for measurement, and was unfitted to disprove the phlogiston theory. It fitted into the theological cast of his mind, and he remained its staunchest supporter.

The English chemistry of the eighteenth century was largely created by leaders of industry who were nonconformist in religion and radical in politics. It was cultivated in the industrial cities, away from Oxford and Cambridge, by a new governing class of industrialists which created its own academies and learned societies. When Priestley left Birmingham, he wrote to Watt of "the pleasing intercourse I have had with you and all my friends of the Lunar Society. Such another I can never expect to see. Indeed, London cannot furnish it." Birmingham provided the most powerful group of minds in contemporary England. Leonard Horner said in 1809 that their impression had not yet worn out, and showed itself "in a spirit of scientific curiosity and free inquiry which even yet makes some stand against Toryism and the love of gain."

The philosophy of the nonconformist and radical industrialists was expressed by Priestley in his Lectures on History. He said that "nothing is so favourable to the rise and progress of learning and the arts, as a number of neighbouring independent states, connected by commerce and policy. This was the condition of ancient Greece, and it is that of Europe at present." He said that the connection between technique and science hardly needed to be pointed out. "It is the same that holds universally between theory and practice." The recent great improvement in technique had "certainly arisen from the late improvements in science." He was of opinion that "speculation is only of use as it leads to practice; that the immediate use of natural science is the power it gives us over nature, by means of the knowledge we acquire of its laws, whereby human life is, in its present state, made more comfortable and happy, but that the greatest

and noblest use of philosophical speculation is the discipline of the heart, and the opportunity it affords of inculcating benevolent and pious sentiments upon the mind."

The violence of the opposition of the Church of England and the Tories to Priestley was due to his unconscious application of the mode of thought of industrialists and scientists to the hierarchical ideas of churchmen and hereditary landlords. His unitarianism was a result of the application of the scientific notion of a uniform substance to the conception of the Trinity. As Veblen has explained, the increasing concern with matter through the development of industry strengthened the feeling of the importance of uniformity.

The concentration of the leading nonconformists, industrialists and scientists in the same centres was not accidental. They formed groups more influential than a collection of individuals. They were bound together by ties even stronger than friendship, as they were largely interrelated by marriage. They were part of one organic social movement, whose progressive energy was drawn from the growing industrialism of the eighteenth century.

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ENLIGHTENMENT

Earth, air, water and fire are the commonest objects of nature, so the Greek philosophers concluded they were the primary elements of which matter is compounded. While belief in this theory was strengthened by two thousand years of tradition, metallurgists, pharmacists and other technicians gradually added new facts to knowledge. The ancient theory was periodically restated to assimilate the new facts. The last of these restatements was made at the end of the seventeenth century by the medicinal chemist Stahl, in the form of the phlogiston theory. The word "phlogiston" is derived from the Greek word for burning, and Stahl used it to describe what he conceived to be the essence of fire. Inflammability was due to a large content of phlogiston. Oil and charcoal were therefore very rich in it. Hydrogen was almost pure phlogiston. Besides explaining the inflammability of this gas, the theory would also explain the very different phenomena of its evolution from mixtures of zinc and acids. The acid drove the phlogiston out of the zinc and left the remains of the metal in the form of white vitriol, which could be obtained subsequently by evaporation. The theory predicted that if the phlogiston were first removed from the zinc, the residue should dissolve in the acid without the evolution of phlogiston in the form of hydrogen. Experiment confirmed this prediction, for zinc, when heated in air, is converted into a powder that dissolves in acid without effervescence.

The theory gives a satisfactory account of qualitative change. It was indeed invented by a pharmacist whose primary interest

in matter was qualitative. The effects of drugs seem to be due much more to intrinsic properties than to the quantity administered, so the pharmacist is primarily interested in intrinsic properties and qualitative differences. The development of pharmacy in the sixteenth and seventeenth centuries, which provided such stimulus to chemical theory, was connected with the new knowledge of drugs and processes brought to Europe through the expansion of world trade. The culmination of the influence of the pharmaceutical tradition is seen in the work of Scheele. His discoveries included oxygen, chlorine, hydrofluoric acid, the preparation of phosphorus from bone ash, arsenic acid, tungstic acid, copper arsenite, the organic acids (tartaric, lactic, uric, prussic, oxalic, malic and gallic), glycerol, aldehyde and casein, and the action of light on silver salts, which is the basis of photography. Scheele combined his unequalled achievement in qualitative chemistry with a firm belief in the phlogiston theory. Priestley followed the qualitative tradition of the pharmacists and retained their belief in phlogiston, but under the influence of the industrial developments with which he was in contact he turned their qualitative methods more to materials of inorganic or industrial interest.

The growth of industry in the eighteenth century caused the results of the primarily pharmaceutical researches of the previous two centuries to be examined in the perspective of industrial ideas. Much more attention was given to their quantitative aspects. The chemists working under the new industrial inspiration tended to believe that all real things could be measured and weighed. Joseph Black, in the new industrial city of Glasgow, was the first to use this attitude with complete success. He elucidated the chemical relations between lime, quicklime and carbon dioxide by means of the balance, the chief instrument of industry. He used the balance to trace the movement of a definite quantity of carbon dioxide through a cycle of reactions that could be repeated indefinitely. The preservation of the carbon dioxide through an endless series of

reactions, and its entrance into chemical combinations in definite quantities, suggested that it was a definite chemical substance. Black therefore asserted that carbon dioxide was not merely a variety of air, as had previously been believed, but was a gas chemically distinct from air. He was the first to prove that gases chemically distinct from air exist, and he had done this by quantitative, not qualitative, analysis. The application of Black's method presently revealed facts inconsistent with the phlogiston theory, but he did not proceed to this work himself. He remained a phlogistonist, though he reflected the new industrial tendency towards materialism in another part of scientific theory. He developed the caloric theory, in which heat is conceived as a form of matter and subject to quantitative laws. His measurements led to the conceptions of specific and latent heat.

Black, Watt, Priestley, Cavendish and their British followers failed to expose the contradictions between the phlogiston theory and the results of the new quantitative analysis and to find a solution to them. They did not submit the new facts to a sufficiently rigorous logical analysis. This was first done by Lavoisier, who brought to the problem not only great ability, but a habit of ruthless and logical thought not possessed by the British chemists. He had acquired this habit of thought from the French intellectual environment, which was different from the British.

The French intellectual environment was a product of French social conditions, so that it follows that these have had a special influence on the foundation of modern chemical theory. Clarity became a characteristic of French thought in the seventeenth century. It evolved during the social and religious conflicts of the previous century, and was a reaction against them. In the sixteenth century the conflicts between feudalism and the new urban civilization broke out in France, as elsewhere, in the form of religious wars. The ideals of the French urban civilization were expressed by Calvin, who had to flee

from Paris in 1533, which was still the centre of feudal Catholic theology. The reaction of the Catholic feudalists against Calvin and reformed theology was led by Loyola and the Jesuit order founded by him. He enrolled his first recruits in Paris in 1534. France became a field of battle between Reformation and Counter-Reformation, and the social disorder caused by this struggle culminated in the massacre of the Protestants in 1572. The resolution of the chaos was achieved by Henry IV. He started as a Huguenot, but became a Catholic in order to make a truce with the Church. He appointed Sully, who was a Huguenot and devoted to order and work, his chief minister, to improve the nation's social and economic organization. Among other innovations, Sully founded the French canal system. As Hauser says, Henry's lucid and balanced intellect was absolutely free from prejudice and guided by reason only. When he was murdered in 1610, the French state was definitely evolving towards bourgeois, and away from feudal, forms.

The tendency continued, and was expressed in sustained effort towards national unity and organization. When Henry died, his son Louis XIII was a minor, and the management of the state passed into the hands of Richelieu. He aimed at the organization of all classes in the state into a unit that could withstand the power of the Hapsburgs and their American gold. As superintendent of navigation and commerce he urged the development of sea power, and deplored the bourgeoisie's hankering after classical education and public office and escape from commerce. Richelieu's unification of the state was continued by his successor, Mazarin, who conducted the government of the country from 1643 to 1661, during the youth of Louis XIV. Louis subsequently disapproved of the subjection of kings to ministers, and said that "nothing is more disgraceful than to see the functions and the mere title of a king in different hands." He was determined to rule himself. But he appointed Colbert, who had managed Mazarin's estates, as his chief minister, and though he made all decisions himself, he

acted on the information of men who had been educated in the mercantile tradition of Richelieu and Mazarin.

The reaction against the chaos and enthusiasm of the sixteenth century seen in this political development was accompanied by a corresponding movement in thought. Malherbe insisted on clear, precise and pure language, based on the usage of polite society. The nobility began to change its manners. It turned its castles into country houses and regulated its boisterous conversation. The Marquise de Rambouillet and other ladies acquired more influence in this environment. They were able to divert conversation to subjects of interest to women. As they were ignorant of Latin and technical affairs, they eliminated from conversation all technical terms used in the schools and workshops. The simplification of the French language was advanced by their influence, and adapted to psychological observation and subtle wit and an easy flow of conversation.

This movement inspired two great events in 1637. The French Academy was officially established in that year, and proceeded to compile a dictionary of the French language consciously based on the speech of the people of Paris, and intelligible to women and the mass of the people. The language was clarified, and became independent of Latin, and was given the quality which made it the future international diplomatic language.

Descartes's *Discourse on Method* was published in 1637, and produced a parallel clarification of philosophy. As Tilley says, his glorification of reason and re-establishment of order and unity in the world of thought were inspired by the same motives as the work of his contemporaries in other fields. In his treatise on the passions, published twelve years later, he insisted that they may be controlled by the will and contended that the will could receive guidance from the reason, which, he believed, could certainly distinguish good from evil. In this, "he was

merely reducing to a system ideas which the drama of Corneille had already made familiar."

The movement for national organization continued while clarification of thought progressed. Louis XIV changed the court from a military into a civil society. He carried a stick instead of wearing a sword, and, as Seignobos remarks, he behaved like a rich bourgeois. Colbert strove to follow the political unification of the country by unifying its economic system. He created police, regulations and taxation to accomplish this, and thereby destroyed the medieval economic system. He believed that the amount of trade in the world was constant, and the prosperity of a nation depended on its securing as large a part of this as it could. He noted that the Dutch possessed 15,000 of the 20,000 ships in Europe, while most of the remainder belonged to England. He encouraged French navigation in order to secure a larger share of sea-borne trade.

When he came into power, nearly all finished goods were imported from Italy and the Low Countries. He stimulated home industries to replace these imports, especially the manufacture of textiles. He made remarkably detailed regulations concerning the type and design of goods, and large factories were created. The Van Robais factory at Abbeville had 1500 workers in 1715.

These industrial and commercial developments were not accompanied by improvements in agriculture. The bourgeois king and his ministers were not interested in it. In 1700, four-fifths of the peasants could not live on their agricultural wages, and eked out their living by handicraft. Fénelon said that France had become "a great desolate hospital, without food." Nevertheless, France was able to support a population of twenty millions, as she possessed a large part of the most fertile soil in Europe. The population of France at the end of the eighteenth century was about twenty-five millions. It was larger than that of the Russian Empire, and nearly three times

as large as that of England, which was nine millions in 1801.

The population provided a large market for the manufactures encouraged by Colbert. The demand for dyed textiles was especially good and gave a big stimulus to the dyeing industry. The best chemists in the country were placed at the head of the state dye works. Berthollet was made director in the eighteenth century, and drew from the dyeing industry the means and inspiration which enabled him to advance the theory of chemistry. In return, he worked out the industrial application of Scheele's discovery of the bleaching action of chlorine, and revolutionized the bleaching industry.

The systematization pursued by Louis XIV and Colbert failed to achieve their aims. They had tried to create a social organization which was as efficient as those of Holland and England without introducing their more advanced political and industrial technique. When their excessive regulation of the national life began to break down, a demand for economic and political liberty arose. The men who were impelled to make these demands had inherited the results of the parallel organization of thought and language of the previous two centuries. The great social movement started in the time of Henry IV split into two parts, and the product of the intellectual side criticized the product of the economic and political side. Voltaire was the foremost of these new critics. He visited England and surveyed its institutions, not unlike an Ionian Greek surveying Babylon. He possessed a sharper and clearer intellect than his hosts, though he belonged to a technically less advanced nation. He returned to France and helped to inspire achievements that surpassed the models he had seen abroad. His *Letters Concerning the English Nation* explained the merits of English culture more simply and clearly than the English could do themselves. His exposition of English religious tolerance, political liberty, and science had a profound effect. Younger followers determined to encourage these qualities in France, and under the leadership of Diderot and Alembert

compiled the French Encyclopedia, which was a universal dictionary of arts, sciences, trades and manufactures. The first volume was published in 1751.

Diderot and Alembert explained the source of their inspiration in their famous preface to the Encyclopédie. They ascribe it to Bacon, Descartes, Newton and Locke, and write: "At the Head of these illustrious Heroes we deservedly place the immortal Francis Bacon, Lord High Chancellor of England; whose works, though justly esteemed, are too little known, and deserve Perusal more than Praise. To consider the just and extensive Views of this prodigious Man; the Multiplicity of his Objects; the Strength of his Style; his sublime Imagery; and extreme Exactness; we are tempted to esteem him the greatest, the most universal, and most eloquent of all Philosophers. . . . It is to this great Author we are chiefly indebted for our Encyclopaediac Plan."

Descartes succeeded Bacon in the construction of their intellectual perspective. He invented algebraical geometry, proposed laws of motion, and submitted scholasticism to sceptical criticism. Nevertheless, thanks were due to the schoolmen who had preserved knowledge and the Greek notion that ideas are not innate but the product of reflection on sensation.

Newton completed the invention of the scientific method, which consists either "in the application of mathematical calculation to experiments; or in simple observation, conducted by method, and sometimes assisted by conjectures for further enquiry; scrupulously avoiding all arbitrary hypotheses."

The reform of writing and language, intended to make reading easy for the gentry, had provided them with an admirable expository prose whose accuracy, purity, and happy choice of terms had been improved by Pascal and the Society of Port Royal.

They ascribed the greatest recent advance in philosophy to Locke. "He may be said to have invented Metaphysics, as Newton invented Physics. . . ." and "He reduced Metaphys-

ics to what, in Reality, they ought to be, an Experimental Philosophy of the Soul." The study of nature, which leads to the development of science, is due partly to necessity and partly to amusement. Many pleasing discoveries are due to curiosity and "an unhappy impotence of acquiring, such as would prove infinitely more useful." Pretence of utility is another motive to the exercise of curiosity. "To have sometimes found a real advantage from enquiries, where at first we did not suspect it, is sufficient to make us regard all curious enquiries as capable of proving useful." Science is the product of this belief, and agriculture and medicine, which "principally gave it birth," are now no more than branches on a great tree that sprang from themselves.

The editors understood the essential part of manual practice in the creation of science, and gave adequate expression to it for the first time. "Should not the inventors of the spring, the chain, and repeating parts of a watch, be equally esteemed with those who have successfully studied to perfect algebra?"

Accordingly, they devoted a new degree of attention to technique. Chambers, in his encyclopaedia, had given only thirty plates illustrating technical processes. They had had six hundred plates carefully made and published in two volumes. Chambers had read books but had rarely visited workshops and seen processes in operation. As these often cannot be understood except from experience, they "were obliged to have recourse to workmen themselves: and accordingly applied to the best in Paris, and in the kingdom of France." They worked machines themselves as a preparation to writing articles on them. In many instances, no written accounts of processes existed.

Lavoisier was born in 1743 and reared in the atmosphere created by the previous century of national and linguistic organization. The Encyclopédie, which was the first great example of organized knowledge, was published during his youth. He acquired from this environment an understanding of the

possibilities of organization, which he applied in civil administration, in scientific thought and experiment, and in exposition.

Lavoisier was born in a prosperous family. His father was attorney to the Parliament of Paris. He was educated at the Collège Mazarin by the distinguished scientists Lacaille, de Jussieu, Guettard and Rouelle. Guettard was the inventor of geological maps and was employed by the government to make an atlas of the nation's mineralogical resources. He invited Laviosier to collaborate with him, and for three years Lavoisier travelled through France collecting and examining minerals. His first chemical researches arose from his analyses of specimens of gypsum, or plaster of Paris.

He made detailed notes of the features of the land and soil, of mines, ironworks, bleaching-works, and stone and plaster deposits; and he kept a careful meteorological diary. Reports of the national industries based on these notes were sent to the Academy. He was elected a member at the age of twenty-five. Thereafter, he reported to the Academy on such matters as the water supply of Paris, prisons, the adulteration of cider, the site of slaughter-houses, bleaching, lamps, smokeless grates, paper, the cultivation of cabbages, the working of coal-mines, the manufacture of starch and white soap, dyeing, inks, glass, alkalies, gunpowder, cesspools, metal refining, and scores of other technical problems.

The government referred inventions to the Academy for expert opinion, and Lavoisier performed the functions of a government chemist and patent examiner.

Shortly after he had become an academician, and still at the age of twenty-five, he purchased a position in the Ferme, the company that farmed the French taxes. These farmers paid the government fixed sums in return for the right to collect taxes. Some of them made profits of one million livres per annum, or about fifty thousand pounds in modern money. The magnitude of these profits was due to a combination of efficient organization and extortion, and drew public opprobrium on

the farmers. Lavoisier received 1,200,000 livres, or sixty thousand pounds, from the Ferme in eighteen years, and was appointed Farmer-General in 1779. He had in addition been appointed to the State Powder Company in 1775, and in that year received quarters in the Arsenal.

Lavoisier improved the manufacture of saltpetre and gunpowder, and made the French product superior to the English. The excellence of the powder was one of the causes of the subsequent successes of the revolutionary armies. He also accumulated large stores of musket powder. This was of particular value for police action in cities, and as there was public unrest at the time, his enemies said that he had accumulated the powder for use against the populace.

Lavoisier made his most famous researches in the laboratory at the Arsenal. He received much assistance from his wife, but he was able to spare only one day a week for experiments. The rest of his working time was devoted to the administration of tax-collecting, powder manufacture, and the conduct of the Academy, of which he became director in 1785.

He spent much of his large income on research, and he did not exceed the rights of exploitation granted him by law. But his acceptance of financial laws widely held to be unjust presently caused him to be condemned by the National Convention.

Lavoisier's association with industry and the Academy gave him a very wide knowledge of the facts of chemistry. He began to compare and organize these facts with the administrative skill that he exercised in tax-collecting and powder manufacture. Instead of concentrating, like Scheele and Priestley, on the discovery of surprising substances by experimental ingenuity, he reflected rather on what was already known. He viewed it as an intellectual administrator, and began a critical examination of the current administration of chemical knowledge, or, in more usual language, of chemical theory. His criti-

cal administrative eye was dissatisfied with the current theory of the elements early in his career.

Following the Aristotelian tradition, water and earth were supposed to contain a common quality, and were capable of being transmuted into each other. This was apparently proved by the powdery substance that appeared in water after prolonged boiling in glass flasks.

Lavoisier had made many experiments on water in his work on the Paris water supply, and he drew on his experience to test the truth of this apparent transformation. He proved by critical experiments that the powdery substance was dissolved by the water out of the glass. This demonstration of the stability of water assisted him to adopt Boyle's definition of a chemical element as a substance not decomposable by any known method. He subsequently made the first list of chemical elements on the basis of this definition.

Lavoisier obtained his proof that water could not be transmuted into earth with the help of the balance. He had noticed that Black had used the balance to trace the movements of a quantity of carbon dioxide through a cycle of chemical changes, so he carefully weighed the flask before and after the boiling, and found that its loss of weight was equal to the weight of the powder that appeared in the water. He saw that Black's results and his own proved that matter is indestructible. He was therefore able to announce the law of the conservation of mass. Further, he saw that if this law were true, weighing provided a general method of analysis which would elucidate all the chemical changes of matter. Chemistry was thenceforth to be based on the study of masses, and mass became the most fundamental property of chemistry. According to this view, substances without mass could not exist, and mass became the first qualification for legitimacy in chemistry. Lavoisier now considered phlogiston from this view. If it existed, it must have mass, and this must be traceable through chemical changes, and

in particular through the processes of combustion. He had a vision of this argument in 1773, when he was thirty years old, and he wrote a memorandum on a plan of research to establish it. He says that he felt impelled to set down in writing an outline of researches on the gaseous substances released in every sort of chemical change, and of the absorption of the air by many substances. Some thought that these gaseous substances were forms of air, others thought they were Black's "fixed air," a third group believed they were emanations of the ultimate parts of innumerable different sorts of substances. The whole range of facts concerning gases was to be carefully re-examined by Black's methods.

"The importance of the end in view prompted me to undertake all this work, which seemed to me destined to bring about a revolution in physics and in chemistry. I have felt bound to look upon all that has been done before me merely as suggestive: I have proposed to repeat it all with new safeguards, in order to link our knowledge of the air that goes into combination or that is liberated from substances with other acquired knowledge, and to form a theory."

Lavoisier elucidated the process of combustion by following very carefully with a balance the changes of weight that occur when metals are heated in air. He obtained conclusive results in 1778, after researches spread over five years. He showed that if mercury is heated in a sealed flask containing air, it absorbs a constituent of the air, and increases in weight by a definite amount which is equal to the weight lost by the enclosed air. The gas left in the flask does not support combustion and respiration. The mercury meanwhile has been transformed into a red powder. If this is removed from the flask and heated, it supplies a volume of gas whose weight is equal to that lost by the enclosed air in the first combustion. When this gas is added to the gas left in the flask after the first combustion, it produces a gas which is indistinguishable in quantity and quality from the original volume of enclosed air. Thus the combustion

of mercury in air is reversible, and can be explained entirely in terms of interaction with a constituent of air which has a definite mass and distinct properties. Combustion in general is therefore completely explicable in terms of this constituent without the hypothetical phlogiston. He discarded phlogiston as an unnecessary multiplication of hypotheses.

He now recast the theory of chemistry in the perspective of this principle. He writes, in his *Elementary Treatise*, published in 1789, that he has imposed on himself "the law of never advancing but from the known to the unknown, of deducing no consequence that does not immediately derive from experiments and observations." Einstein followed the same principle when he discarded the ether from physics, and Heisenberg created the new quantum mechanics by making a theory of what is observable, and excluding the interpolation of hypothetical entities in the explanation of physical processes.

Lavoisier and a small group led by him were able to introduce a rational nomenclature into chemistry after phlogiston had been discarded. He gave oxygen its name, and invented the terminations still used to describe classes of substances. The reform of the language of chemistry was elegantly accomplished by the heirs of the reformation of the French language in the previous century.

Chemistry has been expanded enormously since Lavoisier's time, but it still has his mark. His *Treatise* still reads like an old edition of a modern book. Many fertile ideas have since been introduced into chemistry, but as yet none is as important as the theoretical revolution accomplished by Lavoisier.

Why was this revolution accomplished by Lavoisier rather than by Black and Priestley and the brilliant group of English chemists? Because Lavoisier inherited the habit of clear and systematic thought that was the product of the circumstances of French history, while the Englishmen inherited a habit of ingenuity and compromise from the circumstances of English history, which assisted them in brilliant individual experi-

ments, but inhibited the impulse to explore general theory with ruthless logic and thus discover its limitations.

Lavoisier's success was due not only to his great abilities, but also to acquisition from his social environment of a mode of thought that was particularly well adapted to assist in the solution of the problem with which he was concerned.

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THE RAW MATERIAL OF EVERYTHING

The Greeks and Romans were acquainted with manifestations of electricity and magnetism at least two thousand years ago. The Greeks knew that when amber is rubbed it is able to attract small objects. The Romans were familiar with the attractive power of certain iron ores. These loadstones were found in the province of Magnesia, and their property was accordingly named magnetism. These forms of electricity and magnetism were known for more than one thousand years before they were put to any effective use. They were exploited only by magicians as agents for curing physical and mental diseases. Holding a loadstone in the hand was recommended as a cure for gout, while jilted persons were advised to increase their attractive power by touching electrified objects and magnets.

Virtually no progress in knowledge of magnetism and electricity was made until the possibility of using the magnetic compass for steering ships was discovered about the eleventh century. The vigorous development of trade and navigation at that time, especially in the Baltic and the North Sea, where the skies are cloudy and the altitude of the sun varies greatly with the seasons, stimulated the search for improved methods of steering.

This circumstance caused magnetism to be considered in a new perspective. Hard-headed ocean traders, and men who served them, brought an attitude to the study of magnetism that was different from that of the magicians. They replaced the subjective and gullible interest of lovers by objective and realistic study.

The monk Peregrinus, who had taken part in the crusades and had probably sailed to Palestine, wrote the first known experimental work on magnetism in 1269. The next big advance in magnetism was due to Christopher Columbus, who noticed, two centuries later on his voyage of discovery, that the direction of the compass varies with longitude.

The great navigations focussed intense attention on magnetism, especially in the new maritime countries of the north, such as England. Owing to the esteem in which it was held by the important members of the community who organized colonial expeditions, the attention of men of ability was drawn to it. Queen Elizabeth's personal physician, William Gilbert, studied it from the new practical point of view. He dismissed the alleged magical properties of magnetism as "idle tales and trumpery." He made a series of experiments which proved that magnets have two poles, and that these are different; one seeking the north and the other the south. He showed that like poles repel each other, and that if a magnet is cut into two, each part is a little magnet with its own pair of poles.

He then sought to explore the laws governing the influence of the earth on a compass. He accomplished this by making a globe out of a loadstone, so that it served as a model of the earth. He found that it had two poles. He explored the direction of the magnetic force at various points on the surface with the aid of a small compass, and found that they agreed with those reported by mariners at corresponding points on the earth's surface. He concluded that the earth was a magnetized globe. He found from his model that a magnetic needle points vertically downwards over the poles, and forecast that the needle would point downwards in the northern regions of the earth. His forecast was confirmed by Hudson, the discoverer of Hudson's Bay, in 1608.

While Gilbert was deepening the English knowledge of the chief aid to navigation, his countrymen were founding their first important joint-stock company. This was the East India

Company, which was incorporated in 1600. Gilbert was the first great scientist of modern England, and he published the first great book on magnetism and electricity in the same year, 1600.

Dryden noted the association between Gilbert's researches on magnetism and England's maritime supremacy when he wrote:

> Gilbert shall live till loadstones cease to draw
> Or British fleets the boundless oceans awe.

Gilbert extended his study of attractions to the property of rubbed amber. He described this property as electric, after "electron," the Greek word for amber. He discovered that many other substances besides amber could be electrified. These included glass, resin, sulphur, diamonds, sapphires, and other substances. His list reminds one of the contents of a shop, and suggests how the variety of materials assembled by an expanding trade assists the progress of research. Discovery is virtually impossible without a variety of materials for comparison.

Gilbert proved that electric and magnetic attractions are different, and he found that electrified objects were discharged by the presence of flames. He noted that electrical experiments were more difficult in wet than in dry weather. Gilbert obtained all his electrical effects by simple manual operations. Otto von Guericke, the redoubtable Quartermaster of Magdeburg, who was born one year before Gilbert died, invented the first electrical machine, and made possible the application of power to the production of electricity. His machine gave effects stronger than those obtainable by simple rubbing, and led him to discover the phenomenon of electrical repulsion. Leibnitz discovered with one of Guericke's machines that electricity could produce sparks.

The early Fellows of the Royal Society continued electrical research. Isaac Newton found that electrical attractions penetrated glass, and Hawkesbee showed that if an exhausted glass

globe was electrified, a coloured glow appeared in the empty space.

Progress quickened in the eighteenth century. Gray and Wheeler recognized the difference between insulators and conductors, and transmitted currents along a hempen thread several hundred feet long. Improved forms of Guericke's machine were invented, which would maintain continuous sparks in glass tubes containing air at reduced pressure. This advance was made by scientists living in a mining district in Germany, and proposals to use these discharge tubes as miners' lamps were made in 1744. In the same year Winkler bent a discharge tube to spell the name of a neighbouring duke at night. The discharge tube, which is used today so much for advertisement, is the oldest type of electric lamp, and was invented nearly two centuries ago. It was not successfully utilized in the eighteenth century because a practicable and efficient design of machines for generating electricity had not yet been invented. But the possibility of electricity as an illuminant which possessed certain advantages had been demonstrated.

Much of the curiosity focussed by the strengthening interest in material phenomena in the eighteenth century was devoted to electrical experiments. They were clean and entertaining, and apparently simple. Benjamin Franklin embarked on them in the dry winter atmosphere of Philadelphia. The powerful and clear-cut effects obtained under these conditions assisted him to clarify the theory of electricity and invent the lightning conductor. This was the first contribution to electrical engineering, and it had great psychological besides practical value. It brought lightning, which since prehistoric times had been widely regarded as supernatural, under a degree of human control. This was a splendid contribution towards man's mastery of nature, and it brought Franklin great fame. He used his fame to increase his diplomatic influence and secure support from France for the United States in their struggle for independence. Subsequently, the example of the United States was

a powerful stimulant to the revolutionary movement in France.

The curiosity of the students of electricity varied from the superficial to the profound. Some were interested merely in bigger and better sparks. Others enjoyed giving shocks to their friends. This side of electrical research raised hopes of cures for paralysis and other diseases, and presently received serious study. But the best minds were attracted to electricity by an insight into its philosophical importance. This was very well expressed by Joseph Priestley. He pointed out that it appeared to be a universal property of matter. It was the first universal discovery since that of gravitation. He foresaw its implications and wrote, in the preface to his *History of Electricity:* "Hitherto philosophy has been chiefly conversant about the more sensible properties of bodies. Electricity together with chemistry and the doctrine of light and colours seems to be giving us an inlet into their internal structure, on which all their sensible properties depend. By pursuing this new light, therefore, the bounds of natural science may possibly be extended beyond what we can now form an idea of. New worlds may open to our view, and the glory of the great Sir Isaac Newton himself, and all his contemporaries, be eclipsed by a new set of philosophers, in quite a new field of speculation. Could that great man revisit the earth, and view the experiments of the present race of electricians, he would be no less amazed than Roger Bacon or Sir Francis would have been at his. The electric shock itself, if it be considered attentively, will appear almost as surprising as any discovery that he made."

The next great advances in electrical knowledge came from an attentive consideration of electric shocks. Luigi Galvani, the professor of anatomy and obstetrics at Bologna, like other able medical research workers of the day, investigated the effects of electric shocks on the body. One day somebody in his laboratory was working an electrical machine while dissected frogs were lying on a bench nearby. Another person touched an exposed nerve of one of the frogs very lightly with a knife.

Such a light touch would not normally have produced any contraction, but in this case the frog's legs gave a big kick. The phenomenon was noticed by those present, and it was found that it could be repeated only when the electrical machine was running.

Galvani recognized the importance of the phenomenon, and investigated it for eleven years. He showed that kicks could be obtained if the muscle and the attached nerve were connected respectively to two different metals in contact. He ascribed the effects to "animal electricity" generated in the frogs.

Galvani's remarkable observations were carefully analyzed by the Italian physicist Alessandro Volta, who thought very clearly and had great experimental skill. Volta placed a piece of tin foil on the tip of his tongue and a silver coin on the back. He noted a sour taste when they were connected by a copper wire. If a metal coin was placed on his forehead, and another metal object on his palate, he experienced a strong sensation of a flash of light when they were connected. He concluded that the electricity did not come from the tissues of his body, as Galvani would have supposed, but from the contact of the metals. He wrote that "they are in a real sense the exciters of electricity, while the nerves themselves are passive."

He proceeded to see whether electricity could be drawn from two metals in other ways. He replaced the frog's tissues in Galvani's experiments by various liquids, and discovered that electricity still went round the circuit even when all living material had been removed. He was then led to make the greatest electrical discovery since the discovery of electricity itself. He found that the electrical effect in this experiment, though slight, was continuous. He had discovered the electric current. He did not rest with this. He discovered how to multiply the strength of the current by connecting together a series of metal plates separated by moistened cloth. He sent

an account of his Voltaic battery to the Royal Society of London, which published it in 1800.

The discovery of the electric current aroused enormous interest. Napoleon invited Volta to give demonstrations in Paris, and the Emperor of Austria awarded him with appointments. Within a few weeks, the electric current had been used to decompose water. The youthful Humphry Davy, then twenty-two years old, explored the new phenomenon with zest. He presently decomposed the caustic alkalies, and discovered sodium and potassium. He sent a current through two carbons held in contact, and discovered the electric arc when he drew the two carbons apart. He also employed the arc as an electric furnace to decompose substances. He suggested that mineral deposits should be located by the electric currents which they must produce in the earth, and he invented the process of ionic medication, by suggesting that electric currents should be used to transport irritating substances out of the body.

In spite of all these advances, no definite connection between electricity and magnetism was as yet discovered. The magnetization of steel objects struck by lightning had been noticed, but the phenomenon could not be controlled, and its significance was uncertain. Many experimenters searched for a connection, and at last, in 1819, Oersted of Copenhagen found that an electric current tended to twist a magnetic pole around it. The complete theory of the interaction between currents and magnets was given almost immediately by Ampère, who was the first to point out that the deflection of magnets by currents could be used as a telegraph. Faraday showed in 1823 that a wire bearing a current could be made to rotate round the pole of a magnet, and thus invented the first electric motor. Sturgeon invented the electro-magnet in 1825. He received an award of twenty-five pounds for this. He also invented the commutator. He drew no more benefits from his achievements, and died in destitution.

Oersted's experiment showed that magnetism could be ob-

tained from electricity. Numerous investigators now tried to obtain electricity from magnetism. This proved unexpectedly difficult, and was not solved until 1831, when Faraday discovered electro-magnetic induction. The effect was so elusive because no one suspected that relative motion between the wire and the magnet was necessary. No relative motion seemed to be involved in Oersted's experiment, when a magnetic needle lay still under a constant deflection by a steady current. The relative motion was in fact there, but was supplied by the moving current, which was invisible. It is fundamental in electro-magnetic phenomena, and a century later, from a consideration of the electro-magnetic field, Einstein derived his theory of relativity.

Faraday's success depended on his utilization of the improved electro-magnet designed by Joseph Henry. This young American physicist had applied the engineering methods of James Watt to the improvement of electro-magnets. He systematically tested various designs until he had found the most powerful, and he converted the electro-magnet from a toy into a machine. Faraday would not have obtained a detectable effect unless he had adopted these. Thus engineering methods inspired by industrialism made an essential contribution to his success.

It was now known how to produce light, heat, communication and motion by electricity. The prospect aroused industrial and social hopes, expressed enthusiastically by Davy, Shelley, Joule and many others. Far-sighted men saw that electrical appliances would become a source of profit, and inventors strove to develop them. The social pressure on electrical development was greatest in the richly endowed virgin continent of America, where swift communications were urgently needed both for political unification and for material development. The newly invented railway systems in Europe also created a powerful demand for swift communications, as express trains cannot be safely operated without an almost instantaneous signalling system.

The American portrait-painter Morse and the English physicist Wheatstone invented the first practicable electric telegraphs almost simultaneously. The development of the electric telegraph in the United States assisted stock-market operations, and was pursued with intense energy. The victory of the North in the Civil War implied that business, in opposition to planting, had definitely secured the control of American society. Edison has described the events that directed his inventive energies into telegraphy. When he was a boy of fourteen, selling newspapers on a Detroit train, he heard of the result of the battle of Shiloh, the decisive battle of the Civil War. He telegraphed along the line to the stations that he was bringing news of the battle in his papers. Crowds assembled to buy his papers, and he said that then he "realized that the telegraph was a great invention." He began to learn telegraphy assiduously, and after some years' service in the unsettled post-war Middle West, he was engaged in 1869 on the ticker system of the Gold Indicator Company of New York. This company telegraphed the price of gold to brokers and speculators. Shortly after Edison's arrival, Fisk and Gould attempted to corner all the gold in America, and produced the most notorious speculative crisis in the nineteenth century. C. F. Adams, a great-grandson of John Adams, gave a classical account of this event, and Edison has dictated a not less remarkable account of it. He observed the mob of frantic speculators from the top of the Western Union Telegraph booth in the gold-exchange office. He saw men too excited to write, and five men were required to hold the banker Speyer, who had gone crazy. "The Western Union operator came to me and said: 'Shake, Edison, we are all right. We haven't got a cent.' I felt very happy because we were poor. These occasions are very enjoyable to a poor man, but they occur rarely."

The clearing house was overwhelmed with an inextricable confusion of transactions totalling $500,000,000.

Edison saw that there was money in tickers, and six days later founded a firm for manufacturing telegraphic equipment

and pursuing inventions to order. He thereby created two new professions, for he invented the term "electrical engineer" in the description of the firm, and he was the first man who attempted to professionalize invention. Before him, technicians had invented improvements in the course of their work, but he was the first man who undertook to attempt to invent anything to order. This was a social innovation, as it was an advance towards the transformation of inventing from an erratic art into a science.

Edison's invention of the gramophone arose out of his work on instruments for rapid telegraphy which registered messages on a revolving disc with a pointer. When the machine was run backwards with the disc and its indentations jarring the pointer, it produced a humming noise. This suggested to Edison that such an arrangement might reproduce the human voice, and a successful model was made immediately.

The wonderful invention of the telephone was made almost simultaneously by Bell and Asa Gray in the midst of the strenuous development of telegraphy. Their designs were registered on the same day, but Bell's was registered some hours earlier than Gray's.

The economic and political need to connect America and Europe had stimulated research on Atlantic cables some years earlier. The great physicist William Thomson was drawn into this work, and through it he invented the mirror galvanometer, which established a new degree of sensitivity in electrical instruments. The need for testing the resistance of the copper wire used in the cable led to the improvement of electrical measuring instruments and the formation of the British Association's famous Committee on electrical measurements, which presently inspired the formation of the National Physical Laboratory.

Electrical telegraphy brought into existence a new type of scientist, the technical physicist. No scientific society existed in England for the discussion of his problems, and the Physical

Society of London was founded in 1874 to meet his needs. J. A. Fleming, who subsequently became electrical adviser to Edison and to Marconi, and invented the radio valve, delivered the first paper to the new society in 1874. Sixty-five years later, at the age of eighty-nine, he again addressed the society, and spoke on the conditions of technical physics when the society was founded. He said that the academic scientists, such as Clerk Maxwell, were opposed to the new society and its journal, on the ground that no scientific research was worth publishing if it was unsuitable for acceptance by the Royal Society. This left no medium of publication for the increasing body of men engaged in the scientific problems of telegraphy. The General Post Office had bought the telegraph companies for ten million pounds. This sum indicated the size of the new industry and the relatively large number of scientists employed by it. The introduction of the telephone in 1876 and the electric lamp in 1878 provided the possibility for still larger expansion.

British Government interest in the Atlantic cable was first aroused in 1858, through the Indian Mutiny. A British regiment in Canada had received orders by ship to sail for India. Meanwhile, the Mutiny ended while the ship was on its voyage, and the sailing was unnecessary. But cancellation sent by the next mail boat would not have arrived in time. The authorities were then persuaded to send the cancellation by cable. This succeeded though the cable was faulty, and a needless expenditure of £50,000 on transport was saved.

Though Clerk Maxwell had not sympathized with the founders of the Physical Society, he was the unconscious author of a much greater aid to the development of industrial science. The universities of the Western World had gradually adjusted their teaching of science to the needs of mercantile society. They appointed many professors of mathematics and astronomy in the seventeenth and eighteenth centuries, who taught the science that is most useful to navigators. Isaac Newton

was the greatest of these professors, and for nearly two centuries after his day, when ocean trade was the foundation of world economy, his chief study, mathematical astronomy, was the science that had the highest prestige in university teaching. This prestige still survived at the beginning of the nineteenth century, for it was preserved by the conservative tradition of the universities. The centre of importance in science had, however, moved elsewhere.

Mercantilism had surrendered the initiative to industrialism, and navigation gave place to the steam engine and the telegraph. In parallel with this social movement, mathematical astronomy gave place to heat and electricity. Physics took precedence of astronomy as the senior science. But at Cambridge in the middle of the nineteenth century, astronomy was still the senior science, and the study of heat and electricity had no official place in the university teaching. Maxwell reformed the university science course, and introduced the official teaching of heat and electricity and of experimental physics. The Cavendish Laboratory was founded largely under his inspiration, and was opened in 1874, with him as the first Cavendish Professor of Experimental Physics. Maxwell made teaching at Cambridge suitable for men who were to operate the science of an industrial age. Similar reforms occurred at other universities in Europe and America.

Maxwell's reform appeared to him mainly as a transfer of attention to those parts of science that seemed most promising of important discovery. He did not enquire why heat and electricity appeared to him more promising than astronomy. It was sufficient that he knew that they were so. History has entirely confirmed Maxwell's opinion, though he regarded it as self-evident. It is possible now to see that he was an intellectual instrument of a development determined by the main social forces of his time, while his choice of studies appeared to himself to be determined by the logic of their own develop-

Maxwell's most famous achievement arose out of his study of Faraday's experimental researches on electro-magnetism. He succeeded in expressing Faraday's results in a coherent mathematical theory. Faraday had suggested that electrical influences were transmitted by a wave-motion. Maxwell showed that such a wave-motion would be mathematically consistent with the known facts about electricity, and deduced that the speed of propagation should be equal to that of light. The existence of these electric waves was proved twenty-seven years later by Hertz, in 1887; and radio communication had been achieved. The explanation of certain strange observations now became clear. Joseph Henry had noticed in 1842 that the magnetism of a needle in a coil attached to a lightning conductor was affected by flashes that occurred twenty miles away. He had unwittingly observed radio waves. D. E. Hughes noticed in 1872 that an induction coil would produce clicks in a distant microphone. He presently showed the experiment to G. G. Stokes, who was then the president of the Royal Society, and other eminent scientists, but they were not impressed, and he did not persevere with an investigation of the phenomenon. That also was due to radio waves. There is little doubt that radio waves would have been discovered empirically even if Maxwell had never lived. Great men are not absolutely essential to the progress of science, but they increase its speed.

The first considerable demand for electric power was created by the use of arc lamps. This could not be met economically by Voltaic batteries, so the dynamo was developed to replace them. Arc lights were used in lighthouses, railway goods yards, and big buildings. As they were too powerful for domestic lighting, many inventors attempted to make small incandescent lamps that would serve the domestic user and supply the demand of a vast potential market. The solution of this problem was due mainly to Edison. Besides working out practicable methods of manufacturing incandescent

lamps, he designed and constructed complete electrical power-supply systems. He sold electricity as a commodity for the first time, and had to devise meters for measuring the quantity consumed. He had to invent new methods of insulation, systems of wiring for distribution, and a hitherto unparalleled number of new details. The incandescent-lamp systems required a current supply different from those serving arc lamps, which had to be met by the construction of new types of dynamos.

In addition to these technical developments, Edison made a thorough investigation of the economics of the gas industry, to discover under what conditions competition with it might be successful. This new type of research on all aspects of electrical engineering stimulated the growth of a new type of institution: the industrial research laboratory. Edison's laboratory at Menlo Park, where he directed most of the work on the incandescent lamp and its utilization, was the most striking early example.

One pure scientific observation of first-rate importance was made by Edison in 1883 through his studies of incandescent lamps. As carbon-filament lamps age, some of the carbon is deposited as a film on the inside of the bulb. Shadows sometimes appeared in this film, as if particles that had been ejected by one part of the hot filament had been intercepted by other parts of the filament, and prevented from falling on the bulb. Investigation showed that electricity was indeed leaking from the hot filament. Fleming showed in 1904 that this leak could be used for obtaining direct from alternating currents, and thus invented the radio valve.

While Edison and others were creating the new electrical industry, scientists in the reformed departments of the universities were pursuing researches in the new physics. The incandescent lamps gave the study of high vacua and the electrical phenomena associated with it a new importance. When J. J. Thomson was appointed professor at Cambridge in 1884,

ten years after the Cavendish Laboratory had been opened, he chose the conduction of electricity through gases as the most promising line of research. He did not make that choice because this subject seemed of any practical importance at the time. He was prompted by motives that appeared to him as purely philosophical. But as Maxwell unconsciously adapted university teaching to the higher scientific needs of industry, J. J. Thomson unconsciously adapted experimental research to the same needs. His investigations led to the discovery of the electron in 1897. The implications of this discovery were explored during the first decades of the twentieth century. It became evident that atoms were made of electrons and other electrical particles. Einstein presently identified mass with energy. All matter appeared to be made of electricity; industrial civilization had at length succeeded in interpreting the universe in terms of one of its own concepts. The cosmos was conceived as made of one universal raw material, which is electricity.

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68

THE WORKING CONDITIONS IN WHICH DISCOVERIES ARE MADE

The working conditions in which scientific discoveries have been made may be classified into four types: associated with the exercise of a craft, with teaching, with the pursuit of intellectual amusement, and with professional research. In the first condition, discoveries are made incidentally by technicians in the course of their daily work. Experience suggests how improvements might be made. An immense body of knowledge has been accumulated in this way, and in some techniques, such as agriculture, a large part of the present practice is still based on this sort of knowledge.

In the second, discoveries are made by teachers of technique through reflection on what they are teaching. This condition is characteristic of academic research.

In the third, discoveries are made by wealthy amateurs who seek pleasure in the satisfaction of their curiosity or in the pursuit of intellectual-prestige. In many instances they have combined this motive with a desire for profit. The Marquis of Worcester in the seventeenth, and the Hon. Sir Charles Parsons in the nineteenth century are notable examples.

In the fourth, discoveries are made by professional research workers as the source of their livelihood.

The relative amounts of discovery in these four conditions have varied according to the period. Discovery in prehistoric times was made chiefly by men in the first condition; and in Greek times, in the second and third conditions. In the first two centuries after the Renaissance, the proportion of dis-

covery by men in the third condition increased. During the last hundred years, discovery in the first and third conditions has much decreased; in the second it has increased; while in the fourth, that of professional research, it has virtually begun. Today, scientific discovery is confined almost entirely to men working in the second and fourth conditions—in academic research and in professional research.

Even discovery made in the second, or academic, condition is acquiring more of the characteristics of research done in the fourth condition, owing to the foundation of chairs and appointments in the universities in which research takes precedence of teaching.

The virtual disappearance of research among both craftsmen and wealthy amateurs is due in part to change in the scale of experiments. The apparatus needed in many modern researches is expensive, and difficult to work and understand. A wealthy amateur might require five years' strenuous scientific education before he could enjoy his apparatus. He is more inclined nowadays to make endowments for research rather than do research himself.

The craftsman can do little individual research today because he cannot afford the equipment, and in his daily work is no longer the master of a complete machine. Before the subdivision of labour and the development of big power-driven machinery, the craftsman made most of his own simple machines, and knew all their points as a whole. Now he makes part of a machine designed by another man. He frequently does not understand the complete machine that he operates, and does not know it with the completeness that gives the possibility of suggesting effective improvements.

Individual discovery grows more difficult as individual is supplanted by factory production. The scientist who works in his personal workshop is increasingly supplanted by a team of scientists working in a large laboratory that resembles a factory. The major part of discovery nowadays is made by

scientists organized in teams and following a programme of research in industrial, medical and university research laboratories.

Industrial research laboratories may be divided into two groups: those belonging to private firms, and those belonging to the government. Both groups have evolved from the activities of craftsmen in private and in government employ, and they retain marks of these origins.

The transition of craftsmen's individual research into modern organized industrial research is seen in the activities of the Boulton & Watt firm in the eighteenth century. Watt, Murdoch, Southern and other members of the firm made improvements in the course of their daily work. They also pursued a number of systematic researches on particular problems, such as the accurate measurement of power, and they discussed their problems with Small, Priestley and others, who were forerunners of a type of consulting research scientist. But their various systematic researches did not follow a clearly expressed programme, and such men as Small and Priestley were not formal research consultants and did not regard this work as their profession.

The interest of governments in armaments has had a great influence on the development of science. The first big factories in medieval and modern times were arsenals. As this word is derived from the Arabic, it reveals the influence of Muslim practice on the creation of the forerunners of modern industry. The Italians adopted the institution and the term, and, as has already been mentioned, their arsenals were famous in the time of Dante, and provided inspiration to Galileo. Lavoisier used the resources of the French Arsenal in making the researches that laid the foundation for modern chemistry. The experiments of Rumford on the nature of heat owed their convincing features to the large scale on which they were performed, and this was due to his command of the resources of

the Bavarian Arsenal. He showed that when a cannon was rubbed with a blunt borer, an indefinite amount of heat could be produced during the removal of a negligible quantity of turnings. If the experiment had been made on a small scale, the contrast between the size of the cannon and the quantity of the turnings would have been much less striking.

Though a large part of scientific research in countries such as Great Britain is done in industrial research laboratories, no complete and accessible list of such laboratories exists. In a society based on private enterprise, it is not the duty of the owners of a private research laboratory to publish any particulars of their laboratory and its researches, staff and equipment, or even of its existence. This conviction, characteristic of nineteenth-century industrialists, is gradually being replaced by the belief that complete information on research laboratories, and all other institutions, should be collected and published. This work has begun recently, and is being gradually extended. It is inspired by several motives, including the circulation of knowledge that leads to the more economical organization of industry and research, the discovery that the publication of research activities has considerable advertisement value, and the general social movement towards collective organization.

A list of 120 industrial research laboratories in Great Britain was published in 1936. Of these, nineteen belong to the government.

The British universities and university colleges contain at least four hundred science departments. These are furnished with laboratories which vary much in size and equipment, and some research is done in most of them. Many are old, and even less suited to research than teaching. A good laboratory now costs about £50,000, and the best in universities such as Oxford, Cambridge, Bristol, Glasgow and Edinburgh have cost from £100,000 to £250,000.

The number of scientists in Great Britain is not known exactly, but the Royal Society has a register of 7,000, most of whom have done, or can assist in, research.

The Ministry of Labour has a register of 86,000 engineers and technicians. This also is not complete.

Research on the problems of agriculture, horticulture and fisheries is conducted in at least sixty laboratories in Great Britain. Many of these are part of, or associated with, departments in universities.

Medical knowledge has been advanced by doctors working mainly under two conditions: as individual practitioners, and as teachers in hospital schools. It has not been advanced much by the personal researches of wealthy amateurs, as the subject is not an attractive medium of intellectual entertainment. Medical research as a profession is even newer than industrial research as a profession.

Teachers have contributed relatively more to medicine than to technology. This is owing to the superior status of medical doctors in ancient society. The candidate for a doctor's qualification, unlike the craftsman, was usually of a class that could afford some education. Important medical schools were founded in ancient Greece. These were attached to remedial gymnasia and hospitals, and contributed to a tradition of teaching and research. In Great Britain, some important hospital medical schools and laboratories are still virtually autonomous and independent of universities. Twenty-three London hospitals and medical schools contain teachers recognized by London University, but the students in about three-quarters of them have little contact with the non-medical university students.

The number of medical research institutes in Great Britain whose staffs are primarily engaged in research and not in teaching and treatment is very small. The Universities Year Book lists thirteen.

This retarded development of professional medical as compared with professional industrial research is due to several

causes. The subject is more difficult. Medical research is focussed on the human body, whereas industrial research has immense variety, and those who engage in it can find with greater ease problems that suit their own aptitudes and promise easier solutions. The mechanism of the human body is very complex, and affords immense fields for discovery, but not very many scientists find the best scope for their aptitudes in its very special problems. The majority find that they can do better work in general biology, which presents a wider variety of phenomena and more openings for attack. Other biological material belongs to less advanced organisms and is frequently simpler. It may be susceptible of analysis, and thus provide a clue to the elucidation of more complex human material that could not have been analyzed successfully by direct study.

Lack of endowment has been the chief cause of the delayed development of professional medical research. The majority of patients are willing to pay as much as they can afford for the treatment they receive personally, but they are less anxious to subscribe for research which may be of no immediate aid to themselves, though it may benefit everyone; nor are they willing to press for expenditure on research from public funds. The public pays a large annual sum in fees for medical treatment and is inclined to believe that that is a sufficient expenditure on medicine.

The relatively high income received by doctors often distracts them from research, which is less well paid. For this reason, medical scientists are paid higher salaries than men of equal standing in other sciences.

The organization of research in modern times began in the seventeenth century. In England it was conducted informally by the members of the Royal Society, who drew their incomes from other sources. As the members were under no economic obligation to continue research, they were inclined to make grand schemes for investigating all the universe, but dropped most of them disappointingly soon.

The French Academy, like the French Government, was given a more formal organization. Voltaire contended that this was an advantage, because the Royal Society was lacking in two things most essential to man: rewards and laws. A seat in the French Academy conferred a small but secure salary on a chemist or a geometrician, and gave him the opportunity for sustained research.

The French Academy and its members acted as state advisers on science, technology and patents, and contributed much to the great power of the French state at the end of the eighteenth century. If dominance had been due entirely to science, the French would have entered the nineteenth century with a decisive advantage. But the economic situation and possibilities of England were superior, and these provided the basis on which English science was able to overhaul French science, in spite of its inferior organization. Owing to the accessibility of coal fields and the convenience of water transport, the British industrialists prospered without receiving organized scientific assistance from the state, and they sought scientific advice only when they needed it urgently. They depended on consultants, and did not prosecute systematic researches through their permanent staff.

American industrialists followed the same line at the beginning of the nineteenth century, but their circumstances were considerably different. The country and its economic potentialities were greater, and almost undeveloped. The scarcity of workmen and the promise of quick profit stimulated the invention of labour-saving devices. The introduction of the American sewing-machine in 1846 was a characteristic example of this tendency.

The absence of small workshop industry with a long tradition reduced the opposition to the creation of large and well-organized new industries. Better communications were urgently needed by the scattered population, and by financiers who desired to follow the new possibilities for investment,

which altered and multiplied continually, as quickly as possible. Systems of communication themselves became profitable investments, and possession of them conferred much power on their owners, for communications are the nerves through which society is organized.

In this situation, the telegraph was perfected and the electromagnetic telephone invented. As has been mentioned, Edison organized the first laboratory for systematic invention. This was the forerunner of the famous research department of the General Electric Company of America.

The invention, development and manufacture of the Bell telephone has led to the creation of the Bell Telephone Laboratories, the biggest industrial research institution in the world. It is a striking example of the features and tendencies of modern industrial research.

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69

TWO INDUSTRIAL RESEARCH LABORATORIES

The telephone industry sprang from the utilization of the telephone, which was invented to meet a social need. The invention was made at Boston in 1875 by A. Graham Bell, while attempting to apply electrical vibrating systems to multiple telegraphy. He was the son of A. M. Bell, who experimented on the analysis of speech, vocal physiology and phonetics, and lectured on elocution in London. He learned the technique of teaching deaf mutes from his father, and had emigrated to Boston, where he practised such teaching, besides engaging in telegraphic research. He was appropriately equipped to attack the technical problem he solved so successfully. Financiers and engineers assisted him in the utilization of the invention and created the telephone industry.

Research was the midwife that presented society with its telephonic offspring, and as these have grown up, they have continually extended the sphere of research with which they were originally surrounded. The telephone started in the laboratory and the laboratory has grown with it.

The company that operates the telephone system in the United States still bears the inventor's name. It is the Bell Telephone System. It controls 17,500,000 telephones and employs more than 300,000 persons. It is organized in three subsidiary companies, which respectively maintain and operate the telephones, manufacture the equipment, and conduct research. This latter company is named the Bell Telephone Laboratories and is nominally independent, but does not in fact undertake research for companies that do not belong to the Bell System.

The operating and manufacturing companies formerly conducted their own research departments, but these have been amalgamated into one research institution. This is situated in a block of buildings on West Street, New York City, which were not originally designed for research laboratories and consist largely of converted warehouses. They contain thirteen floors, and the area of working rooms, offices, and workshops is about one million square feet, or twenty acres. A staff of about 4,200 persons is employed, of whom 2,000 are qualified engineers and scientists. The majority are engaged in the solution of routine problems, but about 500 have had a part in the publication of the 1,100 papers on original research that have been issued from the laboratories since 1920.

The technical problems of a telephone system involve many sciences. Good transmitting and receiving instruments must be made of materials which possess suitable magnetic and electrical properties. Their design entails the skilful use of electric currents and circuits and the production of the right acoustic properties. The transmission of currents over thousands of miles of wire presents another series of problems. In addition to securing strong and undistorted messages over great distances, there is the problem of making the service durable. Wires are exposed to weather. The scientist must discover metals that will resist corrosion and wear, and circuits that will suffer the least interference from stray currents produced by lightning and other disturbances. He must discover how wooden poles for supporting wires may be protected from rot, or from boring insects. He must find the explanation and remedy for unexpected break-downs.

The manufacture of the instruments, exchange equipment, switch boards, cables, etc., presents another series of testing and routine research problems. Difficulties that arise in factory processes must be overcome. The research activities mentioned so far refer chiefly to the perfection of standard equipment.

Another division of research is concerned with the development of new operations, such as picture telegraphy and television, and the exploration of ideas, to foresee and provide future methods of communication, possibly of entirely new types.

A large part of the researches made by the staff is published in the company's own journal, whose volumes contain more than one thousand papers. These are classified under the following subjects: acoustics, chemistry, reviews of contemporary physics, crystallography, electron diffraction, inspection, instruments and measurements, insulation, magnetics, mathematical physics, metallurgy, optics, photoelectricity, thermionics, and communication systems, subdivided into picture transmission, power-line telephony, public address, sound pictures, television, train dispatching and miscellaneous, radio, telegraphy, telephone equipment, telephony, and vacuum tubes as circuit elements.

The efficiency of a telephone depends on its adaptation to the peculiarities of human speech and hearing. Callers often receive wrong numbers because their speech is not correctly understood by the operator in the exchange. Harvey Fletcher and his colleagues have analysed these problems in the Bell laboratories, and have much improved the exactitude of acoustic research by the development of better quantitative methods, depending largely on the possibilities of amplification presented by the radio valve. They constructed an experimental microphone and telephone apparatus which would reproduce speech without distortion. They proved that the human ear varies in sensitivity for different tones, and that different ears have different sensitivities. If several people listen to the same speech, each of them hears a slightly different series of sounds, and interpretation of what they hear commences in each case from the consideration of slightly different physiological data, quite apart from the different psychological perspective in which notice of these data is received in the brain,

It has been found that fifty per cent of mistakes in hearing are due to the "th," "f," and "v" sounds, all of which depend on high-frequency sound waves. This work has had great influence on the improvement of sound films and gramophone records, besides telephony, and has proved of value to linguists, actors and doctors. The titles of a few of the papers on acoustics indicate their scope: "The Nature of Language," "Physical Properties of Speech, Music, and Noise," "The Loudness of a Sound and Its Physical Stimulus," "Noise Surveys Out of Doors and in Buildings."

One paper describes the construction of an artificial larynx. A patient suffering from cancer of the larynx had lost his power of speech through an operation. Research was started to see whether he could be supplied with an amplifying mechanism that might assist him to make audible communications. The attempt to assist him was unsuccessful, but the research was continued, and an artificial larynx was contrived which has since restored the power of speech to numerous men and women whose windpipes have been severed through throat operations.

The acoustic technique inspired by telephone requirements has also been applied to the study of heart and lung sounds.

The chemical papers contain many on the properties of carbon, which is used in transmitters, and on the corrosion of materials and insulation.

R. R. Williams has studied the effect of moisture on textiles and rubber used in insulation, and has published papers on chemical methods of preserving wood in poles, etc. He has applied his biochemical technique to the study of vitamins, and has established the formula of, and synthesized, vitamin B_1. This is known as thiamin. Its absence from a diet produces the disease of beri-beri. Pure specimens of the natural substance were first obtained in a Dutch laboratory in Java, after researches spread over thirty years. Williams and his colleagues were aided in the technical analysis by their resources. They

made extracts of rice polishings in a 1,300 gallon tank. The product was dissolved in half a cubic centimetre of water. The original rice polishings contained only about forty or fifty parts per million of the substance. The pure specimen was analysed successfully, and within three years a substance with identical properties was synthesized.

Thiamin is found in hundreds of different tissues in the body, and yet it is not synthesized by animal tissues, but only by higher plants. It is probably made in the leaves and transported to the roots. Cereals contain it in the highest concentration. Its function seems to be connected with the assimilation of sugar and starch. Williams has suggested that seeds contain their relatively large store to enable the germinating plant to utilize its starch in growth before any leaves are exposed, in which fresh thiamin may be synthesized with the aid of sunlight. He has remarked that it seems that man commits a crime against nature when he eats the starch from the seed and throws away that part of the plant which contained the mechanism through which the starch was synthesized.

This research, which is one of the most brilliant in recent chemistry, has great significance for biology and medicine and also for the future of scientific research. It is an example, which will be repeated with increasing frequency, of how a scientist engaged in an industrial research laboratory has been given opportunities for research in directions which have no obvious connection with the laboratory's original industrial aims. The advancement of pure science will in the future depend more and more on the support of the industrial research laboratory.

Radio telephony, sound films, television and many other recent innovations depend on the emission of electrons from metal surfaces in vacuum tubes. The reverse phenomenon, in which metals are bombarded by electrons, produce X-rays. It is evident that the structure of metallic surfaces, which may be of interest for the design of improved instruments, might

be explored by shooting electrons at the surfaces and seeing how they bounce off.

C. J. Davisson and his colleagues started a research of this sort, and in 1920 noticed that the electrons rebounded from a nickel surface in an anomalous manner. The nickel consisted of the usual conglomerate of small crystals. Davisson reinvestigated the phenomenon in 1927 with a single crystal of nickel, and owing to the perfect uniformity of its structure, the anomalies were much more pronounced. The reflected beam was not uniform, but split into a bundle of rays, analogous to a beam of light diffracted by rows of parallel scratches.

De Broglie had suggested in 1924 that electrons possessed wave-properties, and he gave a formula for calculating the size of the waves. Davisson calculated how his beam of electrons ought to behave according to this formula, and found that the result agreed completely with the experimental observations he had already obtained. He had given the first experimental proof of the wave theory of matter. An independent proof was obtained somewhat later by G. P. Thomson. Davisson and Thomson shared a Nobel prize for these achievements.

Many papers on the theory and application of statistics have been published in connection with inspection. Probability theory is used in telephone transmission, in the sampling of manufactured parts for telephones, in the analysis of wearing properties, etc.

Innumerable instruments for electrical and other measurements have been devised, such as forms of cathode-ray oscillographs, analyzers of complex electric waves, and crystal clocks. These are governed by the piezo-electric property of quartz and other crystals, which have an extremely regular natural period of vibration, and may be made to produce an alternating current of extreme regularity.

W. A. Marrison of the Bell laboratories solved the prob-

lems of the construction of the quartz-crystal clock, and produced a timepiece of unparalleled regularity. The quartz crystal oscillated at the rate of 100,000 vibrations a second, and sent out 1,000 time signals each second. These were transmitted by private wire to the Loomis laboratory forty miles from New York, and compared with the timekeeping of a Shortt pendulum clock. As the oscillations of the pendulum are due to gravity, while those of the quartz crystal are not, it was possible to search for variations in gravity by noting variations in the rate of vibration of the pendulum compared with those in the quartz. The comparison revealed a six-hourly fluctuation in the pendulum clocks, which is due to the influence of the moon's gravity.

The crystal clock is also used for standardizing the frequency of radio waves and electric currents.

The need for better materials for magnets, which may be magnetized and demagnetized more quickly and give quicker working, has led to the discovery of new magnetic alloys named permalloy and perminvar. The former has increased the speed of submarine cable telegraphy by five times.

The elaboration of the mathematics required to handle electrical problems has led to the writing of papers on such geometrical subjects as Rotations in Ordinary and Null Spaces, and the Expansion of Laplacian Integrals in Terms of Incomplete Gamma Functions.

The requirements of cable sheathing have promoted studies in the properties of lead alloys. The use of noble metals for reducing corrosion through sparking at electrical contacts, the hardening of copper alloys, the properties of solders, and the characteristics of electrical spot welding are other examples of metallurgical research.

Many investigations on photoelectricity have been made, aiming at the improvement of the photoelectric cell, which has innumerable applications as a mechanical substitute for the eye. Hundreds of papers have been published on the technical

problems of picture transmission, the use of electric power lines as telephone wires, loud-speakers, sound-picture equipment and the electrical and optical systems used in television.

The researches on radio are even more copious. They deal with such matters as transmitters and receivers, the propagation of electric waves over the earth, atmospherics, the ionized regions of the upper atmosphere, and fading.

The system of transmission by carrier currents has been developed. Messages over long-distance lines are not carried by the ordinary current produced by the transmitter. Instead of a direct connection, it modulates, or produces frills in a carrier current. It is possible to send numerous carrier currents along the same wire and sort them out at the receiving end with an electric filter, thus separating the various messages embroidered on the waves of the various carrier currents. The filters which perform this action were invented by G. A. Campbell, and have been developed in the Bell laboratories.

This system has multiplied by many times the number of messages which may be sent through one telephone circuit and has correspondingly increased the amount of service that may be drawn from a fixed system of lines.

The number of messages that may be sent along a cable is greatly increased if it is coaxial. In this construction the wire is held by widely spaced insulators along the centre of a hollow copper tube. The electrical properties of this structure allow the simultaneous transmission of at least two hundred separate telephone messages. As a wave-band of about four thousand cycles is required to transmit the variations of the human voice adequately, the cable will transmit a variety of waves covering 800,000 cycles. This is sufficient for transmission in satisfactory detail of television pictures. Important developments in this direction are to be expected.

Finally, there is the long series of papers on Contemporary Physics by K. K. Darrow. These are expositions of recent advances in such subjects as wave-mechanics, radioactivity, and

cosmic rays. They are written primarily for the information of technical physicists and engineers, to assist them to follow the general direction of physical discovery. Darrow visits the chief physical laboratories in the world. He sees the most important experimental work in progress, and is acquainted with the temperaments as well as the ideas of the men who are doing it. He becomes acquainted with the younger men who assist more famous seniors, and learns the personalities and whereabouts of the future active leaders before their names are prominent in the literature. His knowledge must be of great value to the Bell laboratories, and his papers on the progress of physics are read by many physicists and engineers throughout the world. Thus a service to learning, as distinguished from research, has grown out of telephony. This is an example of the way in which the growth of culture will increasingly depend on the motivation given by the extension of industrial research.

Many of the research rooms are formed by partitions and are rather tightly packed, as the buildings were not originally intended for research. The Bell Company had a plan for building a Research City in the State of New Jersey across the Hudson River. This was to cost thirty million dollars and contain a system of laboratories each designed for its special purpose. The realization of this plan was postponed through the onset of the industrial depression in the United States in 1929.

The amount of research in progress in the Bell laboratories is large, but little of it has no connection with telephony. Even those whose chief researches seem at first sight to have none are simultaneously directing other researches with immediate connection. The distinction between pure and applied research in such an institution has little meaning. Research on the wave-theory of matter might be called pure in a university, but in the best industrial research laboratories it is regarded as a necessary study for the advancement of electrical engineering. It is difficult to estimate the amount of time given to researches

of this sort in the Bell laboratories, but it might be guessed as equivalent to the effort of twenty to forty investigators. It is scarcely possible to say that any particular member of the staff devotes the whole of his time to researches of the sort made in the best university laboratories. A large number devote part of their time to such researches, but very few the whole.

The research laboratory of the Philips Lamp Factory at Eindhoven, Holland, is perhaps the finest industrial research laboratory in the world. It has a beautiful building, designed in the excellent style of modern Dutch architecture. The room and corridors are spacious, clean and quiet, and free from the rush, constriction and dirt often seen in industrial laboratories. It has the calm of a college rather than the bustle of a factory, but is naturally free from academic pedantry.*

The development which led to the erection of this laboratory in 1923 was an outcome of the war of 1914. The Philips firm was making at that time a small number of electric lamps with glass imported from Germany. When the war started, their supply of glass was cut, and they had either to close the factory or to discover how to make the glass. This stimulation to solve its own problems established the tradition of research.

The firm had four scientific research workers in 1914. This group increased to 55 in 1924, 165 in 1931, and 415 in 1936. Of the last number, 40 were physicists, 12 chemists, 53 engineers, 71 assistants, 24 instrument makers, 81 mechanics, 27 glass-blowers, and ten electricians. The laboratory is directed by the physicist G. Holst. Its most remarkable feature is a reflective intellectual atmosphere, unusual in a large industrial organization, and due in part to the virtual absence of administrative staff. The scientific heads of departments have much initiative in discussions with persons outside the laboratory, so that scientific business is conducted directly by scientists rather than by administrators on behalf of scientists.

The most important achievement of the laboratory is the

* This paragraph was written in 1939.

invention of glass and metal seals. Platinum was formerly used for conducting electricity through glass, in X-ray tubes, etc., because it makes a good joint. But it cannot be used in large quantities because of expense. This was a bar to the use of big tubes needing thick wires for transmitting heavy currents. Buowers and Bol searched for metals that would make a good joint with glass, and found certain alloys of iron and chromium were effective. The joints between these alloys and glass are strong enough to resist blows from a hammer, and heavy glass and metal objects made with them do not break when dropped on the floor. Through this invention it became possible to manufacture large radio-transmission valves consuming several hundred horse-power. Van der Pol introduced the use of such valves for short-wave transmission.

The first practicable methods of manufacturing oxide-coated filaments in radio valves were worked out in the laboratory by G. Hertz. The filaments were covered with barium azide, which leaves a satisfactory oxide film when decomposed.

The laboratory has done much research on sodium-vapour lamps. The staff are of the opinion that these lamps offer the possibility of illuminating roads so well that motor head lamps would be unnecessary. It is easy to drive at sixty miles an hour without head lights on Dutch sodium-lighted roads, and the efficiency of the lamps is so high that this degree of illumination may be obtained at an economic cost on a fairly busy road.

Research has also been made on small high-pressure mercury lamps. These operate at pressures up to one ton per square inch, and give an illumination of 180,000 candles per square centimetre. This is more brilliant than the surface of the sun, which gives only 165,000. The temperature of the vapour in these lamps, which are about three-quarters of an inch long and a quarter of an inch in diameter, reaches 9,500° Centigrade. These sources of intense light may be used for the illumination of aerodromes, cinema projection, and other purposes.

Much research has been done on the design of ultra-violet-ray lamps for medical purposes. The performances of lamps of various designs have been tested by the effects of their rays on biological substances. In the course of this work, Reerienk and Van Wyk discovered how to manufacture Vitamin D, which prevents rickets.

The director of radio research is Van der Pol. The theory of oscillations, and especially of non-linear oscillations, which are important in radio circuits, is his special study. He has applied his knowledge to the interpretation of the oscillatory diagrams produced by electrocardiographs, and has deduced from them the existence of hitherto unrecognized rhythms in heart-beats. With Van der Mark, he constructed an electrical model heart, governed by the oscillations of a neon tube, that gave exact imitations of both normal and abnormal rhythms in the human heart.

Since Cockcroft and Walton first accomplished the first artificial disintegration of atoms by machinery at Cambridge in 1932, the Philips engineers have studied how the manufacture of such machinery might be reduced to an industrial process. They have aimed at improvements in design which would ensure reliability and reduce the cost of manufacture, and have succeeded in marketing atom-disintegrating machinery as a commodity. The Cambridge physicists themselves were their first customers, and purchased a two-million-volt set.

In 1936 the Philips firm employed 13,000 workers in its factory at Eindhoven, and a total of 36,000 in its subsidiary firms throughout the world.

Their research laboratory at Eindhoven is the brain of this world organization.

In England, the research department of the Metropolitan-Vickers Company is particularly notable. Aspects of its influence on the progress of research will be noticed in the next section.

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RESEARCH IN UNIVERSITIES

The growth of scientific teaching and research in universities may be illustrated by some features of the development at Cambridge in England. The university had ten chairs of science and medicine in 1816. These were in medicine, mathematics, experimental philosophy, (paleontological) mineralogy, chemistry, botany, anatomy, (petrographical) mineralogy, astronomy, natural and experimental philosophy, and domestic medicine. These chairs were respectively founded in 1540, 1663, 1704, 1724, 1713, 1724, 1707, 1808, 1749, 1783, and 1800, and carried salaries of £40 to £300 per annum.

In addition, there were sixteen lecturerships on algebra, founded in 1710, with stipends of about £20 per annum, and a Barnaby lecturer on mathematics at four guineas per annum.

The colleges at that time had about five hundred Fellows, and of these only part resided in Cambridge. It is difficult to estimate how many of them tutored undergraduates in the colleges in mathematics and science, but the number was probably not more than twenty or thirty, in addition to the university's professors and lecturers.

The Jacksonian Professor of Natural and Experimental Philosophy in 1816 was W. Farish. His lectures are described as embracing a great variety of subjects. "In the original arrangement of them, the Professor conceived that the application of the principle of Natural Philosophy, Natural History, Chemistry, . . . to the arts, manufactures and agriculture of Britain, presented a new and useful field of instruction. After having taken an *actual survey* of everything curious in the

kingdom on such subjects, he contrived a mode of exhibiting the operations and processes that are in use in nearly all of them. Having provided himself with a number of brass wheels of all forms and sizes, such that any two of them can work with each other; and also with a variety of axles, bars, screws, clamps, . . . he constructs at pleasure, with the addition of the peculiar parts, working models of almost every kind of machine. These he puts in motion by a water-wheel or a steam engine, in such a way as to make them in general do the actual work of the real machines, on a small scale; and he explains at the same time the chemical and philosophical principles, on which the various processes of the art exhibited, depend."

In the course of his lectures, Farish explained the natural history of minerals, the theory and practice of mining, smelting, refining and alloying, and he described the manufactures based on them, and arts more remotely connected, such as etching and engraving.

He explained the preparation of sulphur, alum, common salt, acids, alkalies, nitre, and their use in the manufacture of gunpowder, and other processes.

He described the methods of agriculture and the properties and treatment of animal and vegetable products as raw materials for "the great staple manufactures of the country, in wool, cotton, linen, silk." He explained the chemistry of bleaching and dyeing, and the use of mordants and intermediates.

He explained "in general the nature of machinery—the moving powers, such as water-wheels, windmills, and particularly the *agency* of steam, which is the *great* cause of the modern improvement and extension of manufactures."

He described inland navigation, the construction of bridges, aqueducts and locks, and the sciences which assist commerce by the improvement of transport.

"On the whole it is the great design of these lectures to excite the attention of persons already acquainted with the principles

of mathematics, philosophy, natural history, and chemistry, to the advancement of useful arts, and by drawing their minds to the consideration of the most important discoveries of ingenious men, in all parts of the kingdom, to enlarge their sphere of amusement and instruction, and to promote the improvement and progress of the arts."

The lectures were delivered in the rooms attached to the Botanical Garden. The fee for the first course was three guineas; for the second, two guineas; and further courses were free.

Farish's lectures were of the type delivered by Davy at the Royal Institution. Though their aim and content were admirable and intended to prepare men for a part in the development of the rising industrialism, they do not appear to have had much influence at Cambridge. The university was still mainly engaged in training men for the church. Its annual income was £16,000, spent on salaries of officials, professors, the library and schools, printing, taxes, charitable donations, etc.

The number of scientists paid by the university rose from 26 in 1816 to 29 in 1840.

The adaptation of the university to contemporary needs was advanced by the Prince Consort, who was elected Chancellor in 1847. There was no degree examination in science, and one of the first effects of the Commission of 1851, formed under the Prince's influence, was to establish such an examination in 1851.

The syllabus of the mathematical examination included mechanics, optics, spherical astronomy, lunar and planetary theories, hydrodynamics, sound, waves and tides, and elasticity. These were the leading subjects of the mercantile and Newtonian era. Heat, electricity and magnetism were added under the influence of Clerk Maxwell, who was the first examiner to be appointed for these subjects.

This wide range could be covered only by intensive reading

and coaching. A large number of new textbooks were written between 1865 and 1875 to assist the increasing number of students to assimilate these subjects.

While all this reading and writing was in progress, there was still no official laboratory for experimental work on the subjects taught. Like Newton, the professors still conducted their experimental researches in their living rooms, or set up apparatus temporarily in a lecture hall. The contrast between the reading and the absence of practical work could not be overlooked, and the movement for the foundation of a chair and laboratory for experimental physics began. Clerk Maxwell was appointed the first professor of experimental physics in 1871, and by 1874 the laboratory had been financed and built. The funds for the laboratory were provided by the Duke of Devonshire, who was himself a capable mathematician and a relative of the famous Henry Cavendish. The new laboratory cost £8,450.

The foundation of the new laboratory was the occasion of another important innovation; the university appointed its first science demonstrator. This was W. Garnet. Hitherto, the university's official science teachers had been professors only.

In 1874, the university had sixteen professors of science and one demonstrator. The sixteen Sadlerian lecturerships on algebra had been merged into a professorship of pure mathematics, and in 1866 a chair of zoology and comparative anatomy had been founded, seven years after the publication of the *Origin of Species.*

Chairs of physiology and pathology were founded in 1883, and agriculture in 1899.

The need for teaching in organic chemistry became acute. Dewar asked Hofmann in Berlin to recommend an organic chemist. He sent S. Ruhemann, who arrived in Cambridge in 1885 at the age of 26. Ruhemann found that the university did not possess a laboratory for organic chemistry. He presently found a small dark room where he could lecture and

demonstrate to a few students. There were no stores of apparatus, and the available reagents were impure. He drew attention to this situation, and the authorities said that he could have £25 to go to Berlin and secure all the necessary material.

The part of Hofmann in this incident of the starting of research in organic chemistry at Cambridge again recalls the influence of the Prince Consort on science in Cambridge and England. Hofmann was originally invited to England through the Prince. Perkin discovered aniline dyes while working with him. When Hofmann returned to Germany, he became the chief agent of his country's pre-eminence in chemistry and the dyestuffs industry. His dispatch of one of his best students to the study of organic chemistry in Cambridge would not have occurred without his English connection, so, after the Prince's death, and indirectly, his influence had again been felt.

In 1900, Cambridge had twenty professors of science, and the number of junior staff had increased from one to twenty-eight. These consisted of four readers, twenty-one demonstrators, and three assistants to professors. The total of forty-eight science teachers in 1900 had increased to 212 in 1938. There were then 34 professors of science, 16 readers, 107 lecturers, 46 demonstrators and 9 assistants to professors. This does not include science fellows of colleges without university appointments, laboratory assistants and mechanics.

This growth of personnel was accompanied by corresponding increases in endowments for laboratories. The university staff of the Cavendish Laboratory increased from two in 1874 to fourteen in 1938, and the number of research students had increased to more than thirty.

The laboratory buildings were extended at a cost of £4,000 in 1896, and again, in 1908, at a cost of £7,135, including £5,000 donated by Rayleigh from his Nobel Prize money. This series of relatively small buildings formed an odd conglomeration of research and lecture rooms, workshops and corridors.

So far, when expenditure had been made, it was spread over the whole teaching and research activities of the laboratory, and was not devoted to special researches. Much of the apparatus used for research in 1874 and the early days was also used for teaching. Galvanometers were temporarily disconnected from the apparatus set up in the research rooms for use by students during their practical classes. The equipment in apparatus and workshops slowly increased, but was still quite small in 1914, though in the previous thirty years, fifty professors of physics had been trained, including Rutherford, the Braggs, C. T. R. Wilson, O. W. Richardson, Callendar, and Langevin; the electron had been discovered; and the first advances towards the elucidation of atomic structure had been started.

The scale of experiments still remained small for the first few years after Rutherford's appointment as Cavendish Professor in 1919. Expenditure on apparatus was conceived in units of £50, and there was intense competition for the use of these small sums by research workers who were then well-known, and have since become famous.

A new scale of experimentation and expenditure arose out of the work of P. Kapitza. He began research in 1922 on a method of producing intense magnetic fields by short-circuiting a battery of accumulators through a coil. It was successful, so he suggested that still more intense fields might be made by short-circuiting a dynamo through a coil. The design and construction of this machinery was far more expensive than that of any previous single piece of apparatus used in the Cavendish Laboratory. It cost many thousands of pounds, and could not have been done without large grants, which came especially from the Department of Scientific and Industrial Research. The late Lord Balfour was then the Minister to whom the Department was responsible, and he was active in promoting support for these large-scale experiments. The new scale of expenditure arising out of Kapitza's work was confirmed in

1930, when the Royal Society granted £15,000 for the construction of a laboratory for research with strong magnetic fields at low temperatures. This was an innovation in the Cavendish tradition, as formerly no part of this size and cost had been built purely for research, unconnected with teaching.

Research on radioactivity was still confined to the utilization of natural radioactive substances. These existed in very small quantities, and the apparatus designed to investigate them remained for a long time on the small scale. But in the thirty years of research that had passed since the discovery of radioactivity in 1896, most of the experiments practicable with existing small apparatus had been performed. Progress depended on the submission of radioactive substances to more powerful modifying forces. Research had passed to the study of the structure of the nucleus of the atom, and forces of a new degree of strength were needed to elucidate its inaccessible features. The disintegrating radioactive nucleus emits particles in groups with definite speeds. The accurate determination of these speeds was necessary for the advance of the theory of the nucleus, and it is most conveniently obtained by deflecting the emitted particles in a powerful magnetic field. A suitable big magnet did not exist at Cambridge for the analysis of rays of emitted helium nuclei, and the experiment was first performed successfully with the great electro-magnet at Paris.

In this general situation, new types of knowledge and ability were required in the Cavendish Laboratory. Kapitza was an electric engineer by training, and his success with the short-circuiting dynamo was due to his command of engineering design. J. D. Cockcroft assisted him in this work.

Cockcroft was an electrical engineer who had graduated at the Manchester College of Technology under Miles Walker, and had entered Metropolitan Vickers, Ltd. After the war of 1914–18, he returned to the firm, and in his spare time he and another engineer made researches in electrical engineering under Walker's direction. The Institution of Electrical Engineers

had collected a sum of money to celebrate the end of the war, and decided to found a scholarship to assist electrical engineers to continue research. The first award was made to Cockcroft.

He went to Cambridge, and took a course of applied mathematics, and engaged in further research. In 1928–30 he had a table in a corner of the shed where Kapitza's dynamo was erected, and quietly and obscurely worked there. The dynamo was manufactured by Metropolitan Vickers, where he was formerly an engineer, and he did invaluable work in interpreting the needs of the scientists to the manufacturing engineers, besides joining in the research. He assisted C. D. Ellis and H. Kershaw to design a large permanent magnet for the separation of the electrons emitted from disintegrating atoms into groups. It was possible to adopt a permanent magnet for this purpose by utilizing the properties of the new cobalt steels. The magnetic field in these steels may be fixed by a temporary current, and later destroyed and fixed at a different strength by another temporary current. The permanence of the field at a suitable strength for any interval of time obviates the consumption of a continuous current that would be necessary in an electro-magnet, and it also removes the trouble of keeping such a current constant. This magnet was made by Metropolitan Vickers.

Cockcroft also assisted Kapitza in the design of the equipment and building of the new laboratory for research on strong magnetic fields at low temperatures. They constructed a hydrogen liquefier in which part of the cooling was done with commercial hydrogen. This made the cost of liquefaction less than if purified hydrogen had been used throughout.

While Cockcroft was assisting in these various works, he was building a small high-tension apparatus in a corner of a room which has now been taken over by the department of physical chemistry. He had a few big insulators, transformers, and glass tubes, of the type used in the transmission of high-tension electric currents. He was attempting to construct an

apparatus for producing streams of protons accelerated to a high speed by a strong electric field. He was aided in this work by T. E. Allibone of Metropolitan Vickers. The firm also presented much of the material, which consisted of standard electrical-engineering products.

The apparatus was perfected, and in 1932 Cockcroft, with E. T. S. Walton, successfully disintegrated atoms with it. This was one of the supreme experiments in science, because it had reduced the transmutation of the elements to a process that could be conducted with machinery of an industrial type, and so had brought it within sight of exploitation for the benefit of man.

The experiment is the trigger which has released the full pressure of American industrialism on the development of science. America leads in electrical engineering, and now that physical research depends so directly on electrical engineering, America has assumed the lead in experimental physics. This has happened through E. O. Lawrence's invention of the cyclotron. The construction of such a machine, which produces swift particles by whirling them round a magnetic field, like stones on the ends of bits of string, and then letting them go, had been considered by others, but was believed to be impracticable. Even now, seven years later, everyone except Lawrence has had great difficulty in making cyclotrons work.

When Kapitza did not return from the Soviet Union in 1934, Cockcroft became the virtual director of the Mond Laboratory, and mastered the subject of low-temperature physics, which is quite different from electrical engineering.

The Metropolitan Vickers Company has made an essential contribution to the recent achievements of the Cavendish Laboratory in atomic physics. Many branches of physical research in universities can no longer be undertaken without the collaboration of the industrial-research laboratories of such firms and the intermediation of engineering physicists, of whom Cockcroft is so distinguished an example.

The Metropolitan Vickers firm has recently made cyclotrons for J. Chadwick at Liverpool and also for the Cavendish Laboratory. It has constructed the improved Bush calculating machine used by D. R. Hartree at Manchester University. This machine cost more than £4,000. It has also constructed the special air-cooled magnet used by P. M. S. Blackett in the same university. This cost more than £1,000.

The success of all the researches on atomic disintegration by electrical machinery has depended on a technical invention made in the Metropolitan Vickers Laboratory by C. R. Burch. In 1930 he showed how to manufacture oils of very low vapour pressure by the molecular distillation of lubricating oils. Hitherto, high vacua had been made by removing residual gas from a vessel with a blast of mercury vapour, and then condensing the mercury vapour with liquid-air cooling. The new oils were up to ten thousand times less volatile than mercury, and when they were used in vacuum pumps instead of mercury, they left a high vacuum when condensed only with water cooling. Thus they eliminated the need for liquid air in producing high vacua. Vessels could be evacuated continuously, and the application of drastic heat treatment to remove the remnants of gases sticking to the inside surfaces became unnecessary. It became possible to obtain good vacua very quickly in vessels connected to pumps merely through ground-glass joints, without sealing the glass by flame. Burch prepared greases from the residues of his distilled oils, which had an extremely low vapour pressure and could be used for plastering the ground-glass joints and swiftly making them gas-tight.

The discovery of these oils and greases has proved of great economic importance, for besides facilitating the manufacture of small valves and X-ray tubes, it has made the use of big demountable valves and tubes practicable. Big valves are needed for transatlantic telephony, and big X-ray tubes for cancer treatment. The use of such big apparatuses would not be practicable unless they could be taken to pieces, repaired, and

re-evacuated quickly and inexpensively. That would have been impossible with mercury pumps.

Similarly, it would have been very difficult to accomplish the disintegration of atoms with the assistance of big vacuum tubes unless these tubes could be opened, the experimental targets inside rearranged, and the tubes re-evacuated expeditiously.

The introduction of Burch's oil so facilitated evacuation that the time of one experiment with the atomic-disintegrating apparatus was reduced from about a fortnight to one hour. This enormously increased the possibilities for trying various experimental arrangements, and finding the successful one. Burch introduced the oils in 1930, and atoms were disintegrated with the aid of big high-tension vacuum tubes for the first time in 1932.

Research on atoms, cosmic rays, and other subjects of modern physics has been greatly assisted by amplifying devices which utilize electrical instruments and circuits developed by the radio industry. With these devices it is possible to count automatically over any interval of time, from a ten-thousandth of a second up to a year or more, the number of particles emitted during atomic disintegrations. This established a new order of accuracy and scope in investigating disintegrative processes. The development of the use of these devices in atomic researches at the Cavendish Laboratory was due especially to C. E. Wynn-Williams, who had a remarkable mastery of this branch of light electrical engineering.

The conduct of physical experiments on an engineering scale created the need for a new scale of endowment. The cost of units of apparatus had risen from the order of £50 in 1925 to £500 in 1935. In 1936, Lord Austin presented £250,000 to the Cavendish Laboratory to enable it to meet the new need. A two-million-volt high-tension laboratory has been constructed, a fifty-ton cyclotron installed, and a large block of research rooms is under construction.

The researches in the Cavendish Laboratory belong to the most advanced and purest part of experimental physics. Rutherford's successor, W. L. Bragg, is adding the study of the structure of solids, and especially metals, to the programme of research. This work is being assisted with funds from the British Iron and Steel Federation, an association of firms engaged in the iron-and-steel industry.

The Cavendish Laboratory is devoted entirely to pure science, but its researches show how an ancient university has adapted itself to modern interests. These interests, or social needs, have also secured more direct attention by the creation of special universities to serve them. These are technical universities. The Massachusetts Institute of Technology is one of the most striking examples. It was founded at Boston in 1861 during the American Civil War, and was intended to serve the whole of the United States. Its aim was to educate men for the industrial civilization whose domination was assured by the victory of the North. Its foundation occurred at about the same time as Clerk Maxwell's movement for the reform of science teaching at Cambridge in England. After the Cavendish Laboratory was opened in 1874, the methods of teaching practical physics evolved by Pickering at the M.I.T. were adopted.

The institution now has an endowment and plant worth £10,000,000. George Eastman, who invented the Kodak camera and photographic film and created a new industry, gave £4,000,000 of this. Its present magnificent buildings were erected in 1916 on a site of eighty acres beside the Charles River basin. The city of Boston, and the neighbouring town of Cambridge, which contains Harvard University, are on the banks of the Charles River, and formerly suffered from flooding. This trouble was removed by a splendid piece of municipal engineering. A barrage was built across the mouth of the river, which created a basin or river-lake several miles long. The new buildings of the M.I.T. and Harvard are on different parts of

the banks of the basin, those of the M.I.T. being nearer the centre of Boston. The students from both institutions have excellent sailing and boating facilities, and on hot summer days can read in dinghies while drifting in the cool air over the water.

The M.I.T. has about 2,600 students, of whom 500 are graduates, and a teaching staff of five hundred. The latter includes thirty-one professors of chemistry, twenty-eight of engineering, and twenty-five of physics. They are divided into three grades—professor, associate professor and assistant professor—in about equal numbers. The senior grade does not contain all of the eminent scientists. For instance, in 1938 the junior grade included such physicists as Van de Graaff, M. S. Vallarta and F. W. Sears.

The work on calculating machines by Vannevar Bush is perhaps the most remarkable done at M.I.T. Until recently he was the vice-president, and is now the president of the Carnegie Institution of Washington. Bush is a lean, keen man of evident genius and humour, who must have been stimulating to good students and disconcerting to lazy ones. His work on the invention of numerous types of calculating machine is not a form of gadgeteering, but the pursuit of a philosophical idea. He considers that the greatest mathematical discoveries have arisen in the past out of the use of mechanical aids to calculation, and similar discoveries inspired by calculating machines may be expected in the future. The invention of the Arabic system of numerals and a symbol for zero arose out of the form of the abacus. He contends that the mechanical fact that it is convenient to mount wires parallel to a frame inspired the invention of positional numeration and zero. The formal mathematicians of classical times declined to use the plebeian abacus. They stuck to their cumbersome notation, while men of trade, with a mechanical aid, produced the most far-reaching of mathematical inventions. The formalist's insistence that ruler and compass were the only tools worthy of the gentle-

man-scholar directed the attention of the learned for centuries to insoluble problems, such as the trisection of an angle with these instruments. As the decimal system arose out of the abacus, so a new mathematics may arise out of the development of calculating machines for the assistance of engineers and business men.

The work of Van de Graaff on high-voltage generators is very well known. He has built a machine with two aluminium discharge spheres fifteen feet in diameter, mounted on insulating cylinders thirty feet high. One sphere is charged positively and the other negatively, and sparks jump between them at 10,000,000 volts. Van de Graaff is also interested in operating electrical machines in high vacua. The insulation thus obtained allows compactness in design, which yields convenience in use and economy in manufacture.

Aerodynamical research is another strong department at the M.I.T. Several wind-tunnels are used, and aerological observations, including a daily flight to 20,000 feet for data, are made in collaboration with the United States Air Corps.

The Cavendish Laboratory and the Massachusetts Institute of Technology illustrate how educational institutions provide training and knowledge for modern society. In addition to the industrial and university research laboratories, there are some independent research laboratories unattached to either.

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RESEARCH AS AN INDEPENDENT SOCIAL ACTIVITY

Research arose incidentally out of the work of the craftsman and teacher. It has begun only recently to attempt to emancipate itself and pursue its own life as an autonomous social organism, with its own factories, or laboratories. The most impressive manifestation of this development, both in achievement and in fate, is the Kaiser-Wilhelm-Gesellschaft zur Förderung der Wissenschaften. It possesses some thirty institutes designed entirely for research.

This society was founded in 1911 by Wilhelm II, under the inspiration of German scholars and scientists. Its aim was derived from the project of Wilhelm von Humboldt, the Minister of Education in Prussia at the beginning of the nineteenth century, who moulded the features of the German system of education. Humboldt combined Prussian ideas of organization with French enlightenment, and through the latter drew inspiration from Francis Bacon. The institutes of the Kaiser-Wilhelm-Gesellschaft are a partial realization of Bacon's aims.

Humboldt said that the German universities and academies should be helped by a third type of institute, independently engaged in discovery.

The Kaiser-Wilhelm-Gesellschaft started with two hundred members, most of whom were industrialists, bankers, business men, etc. These subscribed funds which provided the society with a private endowment, and gave it the means to pursue its own research policy, free from direct control by the state.

The new institutes were devoted to three purposes: the pro-

motion of new fields of enquiry which could not be conveniently started in universities, the provision of temporary or permanent opportunities of research for academic scientists overburdened with teaching, and the training of graduates in research before they had entered an academic career.

The society adopted the principle of an evolving, and not a settled, research programme to achieve these purposes. Its first president, von Harnack, said that the society "must not build institutes and then seek for the right man, but must first find an eminent scholar and then build an institute for him." It consciously watched for innovations in learning, and sought to aid those that seemed most promising. It offered to build for the scientist who had created a new branch of research an institute designed to suit his needs, and provide him permanently with the best conditions for work. When the scientist died or retired, the institute was to be closed or adapted to the needs of a scientist working in another field, but no successor in the same field was to be appointed unless there was a clearly outstanding candidate.

The realization of this scheme was hindered by the war of 1914, but after the war it was prosecuted with energy, in spite of poverty. The number of the society's financial supporters had increased by 1930 to seven hundred, and included the government of Germany and local governments. The state donations were given without conditions, so that the initiative of the society remained legally free. Contributions were received from all the Prussian provinces, the greater towns and districts, and the principal trade unions, besides industrialists and others.

Motions in the Reichstag for the support of the society were invariably supported by all parties, from the National Socialists to the Communists. The statement by Harnack in 1910 that "armed defence and science are the two strong pillars to support the greatness of Germany, the care of which must never cease or stand still" was widely approved. After the

war, when Germany's military forces were limited by treaty, there was an extra effort to strengthen the other pillar, "to hinder the undoing of Germany."

The policy of the society was guided by a senate, one half of which was elected by the members, and the other half originally nominated by Wilhelm II and then, during the period of the Republic, by the German and local governments. The senate elected the presidents and executive committee. Harnack remained president until his death in 1930. Krupp von Bohlen was then first vice-president, and the board included Planck and Duisberg.

The Ministers for Internal Affairs, and for Science, Art and Education in Prussia were entitled to send representatives to all meetings. The latter position in 1930 was held by Becker, the Republican statesman and Islamic scholar. After Harnack's death, Becker and Planck became candidates for the presidency. They received support, respectively, from various scientific groups, but there was also a political alignment. The Republicans supported Becker, and the Nationalists Planck; and Planck was elected.

In addition to the senate there was a scientific advisory council, containing all the senior scientists working for the society. It was organized in three sections: for biology and medicine, chemistry and physics, and the humanities. The presidents of these sections helped to choose scientists and subjects to be aided.

The work of the society was arranged under the divisions of theoretical and applied science, which were to be pursued in two series of institutes. The first institutes in the series for theoretical science were devoted to chemistry, physics, zoology, botany and medicine. An institute for biology was built at Dahlem. This contained six lesser institutes, or departments, as it was found that biology might be advanced more easily by a collaboration of a group of independent workers than by the work of a big institute devoted to a single branch of

biology. The independent departments in this institute were directed at various times by Correns, Goldschmidt, Hartmann, Mangold, Warburg, Meyerhof, Herbst, Spemann and A. Fischer. Separate institutes were built for Neuberg for biochemical investigations, and for Eugen Fischer for inquiries on human heredity and genetics, and an institute for Abderhalden for physiological chemistry was established at Halle.

Two institutes for chemistry were built at Dahlem; one, for physical chemistry, was directed by Haber, and the other, for general chemistry, was directed at various times by Willstätter and Hahn.

An institute for physics, directed by Einstein and von Laue, was established in Berlin, and one for aerodynamics at Göttingen.

In medical research, an institute for Wassermann for work on experimental therapeutics was established at Dahlem. One for Oskar and Cécile Vogt on brain research was built at Berlin-Buch. The society undertook the support of Kraepelin's institute for psychiatry in Munich. It built an institute at Heidelberg for the application of physics, chemistry and physiology to clinical research. This is at present directed by R. Kuhn, who was awarded the Nobel Prize for chemistry for 1938.*

The institutes in the second division were devoted to applied science. These included the institute for coal research at Mühlheim, directed by Franz Fischer. A second was built at Breslau to deal with the problems of Silesian coal. This was directed by F. Hofmann, who also made important contributions towards the chemistry of the synthesis of rubber.

A great institute for research on iron was built at Düsseldorf, and another for the study of light alloys at Berlin-Lichterfelde. Institutes for the study of silicates and textile fibres have been built at Dahlem. The first papers of Bergmann, Mark and Polanyi were issued from the latter. An institute for

* This paragraph was written in 1939.

leather research was established under Bergmann at Dresden, and another for hydraulics at Munich.

The applications of biology were pursued in a great institute for industrial physiology built at Dortmund, and in an institute for animal breeding established near Berlin, and directed by Baur.

The society assisted various smaller laboratories for hydrobiology at Plön and Lunz and Rovigno; meteorological stations in the Austrian mountains; and a bird observatory in the Kurische Nehrung, where the study of the flight of birds by the ring system was begun.

The society jointly founded the laboratory on the Jungfraujoch, so much used by students of cosmic rays. It also founded institutes for history and law, and possessed a library of art history in the Palazzo Zuccari, in Rome.

The group of a dozen institutes at Dahlem produced an extraordinary concentration of research ability. A hostel, named the Harnack House, was built for foreign scientists visiting and working in the institutes, and rest rooms, libraries and refectories were attached for the comfort of the permanent staffs. About two hundred research scientists from the various institutes met in the Harnack House and exchanged ideas. Anything new that happened anywhere in the scientific world was known almost immediately by this varied body of workers, and its possibilities were eagerly discussed. This was one of the causes of the rapidity of the advance of science in Germany at that period. A similar effect was seen in the colloquium on physics at Berlin University. Many of the research workers at Dahlem delivered occasional lectures at the university and attended its colloquia. The concentration of talent produced an accumulation of knowledge, and the assembly of wits an intellectual competition. Einstein, Laue, and others fired the flame of discussion, and it darted swiftly to new regions of thought.

Haber led an equally brilliant colloquium at Dahlem on

chemistry. He was the most characteristic figure in the development of science in Germany during the last generation. He was a hard, generous and lively man, whose achievements had been accomplished through untiring pursuit of detail and a driving capacity in organization. He was nearly always animated, and either smiling or severe. He had a sense of the dignity of his position, and a childlike vanity. He had the strongest personality among German scientists, and had something of the manner and authority of a Rutherford. One could often hear German scientists say: "Haber is our greatest man." He raised the standard of scientific discussions by vigorous criticism, and he hated humbug and superficiality from any quarter.

In spite of his love of German ways, he believed his countrymen were apt to be rude. He therefore cultivated the most courtly manners. Visitors to his house at Dahlem, which was not large, but decorated with extremely elegant Chinese and Japanese works of art, were most graciously received. He sometimes invited Englishmen to tea from an exquisite silver service on a rare lace table cover, while he drank coffee and glasses of Fachinger mineral water. He started conversation in a very quiet and polished style, and considerately excused points of view contrary to his own, but after some time, as his enthusiasm arose, he could not restrain the natural vigour of his expression of opinion, and perhaps after an hour, if he was deeply interested in his subject, he had forgotten his theories of style, and was speaking and gesticulating vehemently. A stranger entering the room at that moment might have been surprised to learn that he was engaged in nothing more than an academic discussion.

Haber solved the problem of the synthesis of ammonia from nitrogen and hydrogen or intermediary substances. He began to investigate this problem in 1904. Nernst and others made important contributions to the solution, but success was not obtained until Haber experimented with mixtures of the gases at temperatures of 550° C. and pressures of 200 atmospheres,

working conditions that were far more severe than had ever been used before in large-scale operations.

This research was done at the Technical University at Karlsruhe. It was not encouraged by the German chemical industrialists, as they were interested in synthesis by the electric arc, which had been started in Norway. Nevertheless, in 1909, Haber demonstrated the production of ammonia by his process to Karl Bosch, an engineer of the Bavarian Dye Company. Bosch immediately started the construction of a synthetic-ammonia factory, and after three years, in 1912, the factory was in regular operation. Haber continually advised Bosch, but he had little part in the solution of the new engineering problems presented by operations on an industrial scale. This feat has been described as the most difficult and brilliant ever achieved in chemical engineering, and its social effects were immense.

When the German Army invaded France in 1914, its leaders had given little consideration to questions of supply. They had not expected a long war. They knew that they could obtain sufficient nitrates for explosives from the coke-oven plants of the coal industry, but they had not foreseen that there would be an additional demand for nitrogen fertilizers. But the march on Paris was halted, and the nitrates for fertilizers, which had formerly been imported from Chile, were cut off. If the German Army had not unexpectedly captured 50,000 tons of nitrates in Antwerp, Germany would have been in a very difficult position as early as 1915. When the significance of the situation was perceived, the Raw Materials Department of the War Ministry was placed in Haber's charge. He increased the production of ammonia by the cyanamide process tenfold, and synthetic ammonia from 6,500 tons in 1913 to 200,000 tons in 1918.

The Battle of the Marne convinced the German Command that new weapons would be required to wage successful trench warfare. They consulted Nernst on the possibilities

of gas, and afterwards Haber. The Command presently requested Haber to prepare material for an attack by a cloud of chlorine gas. He did this, and in six months also devised an ingenious gas mask. He was made chief of the Chemical Warfare Service in 1916. Thenceforth he directed the research, supply, and training of personnel. His department introduced mustard gas in 1917, and tried hundreds of other substances. He managed all this organization, and the large number of scientists and soldiers, with extraordinary executive ability.

In 1911, the Kaiser-Wilhelm-Gesellschaft had invited Haber to direct an institute for physical chemistry, after his triumph with the synthesis of ammonia at Karlsruhe. The institute was opened by Wilhelm II in 1912. When the war started, Haber immediately placed it at the disposal of the War Ministry, and many of the researches on chemical warfare directed by him were done there.

He had intense confidence in the certainty of victory, and was profoundly shaken by the defeat. In addition to this, he was subjected to widespread and ill-informed abuse as the inventor of gas warfare. This accusation was as stupid as it was ill-founded. Haber subsequently made interesting comments on the psychology of the critics of gas warfare. He remarked that gas, submarine, and air warfare were the three chief innovations in military technique in the war of 1914–18. The introduction of new military weapons has always been condemned as barbarous. Gunpowder and artillery were condemned as fiercely in the fourteenth century as gas in the twentieth. The submarine has been condemned less than gas because it operates out of the sight of large numbers of people, while the air weapon has earned the greatest honour because it has renewed "the heroic age of single combat, that had almost died in modern war."

Haber received the most severe blows in his personal relationships through his work in gas warfare. Then his enormous effort and personal suffering were followed by the defeat

in war, which struck at his pride in Germany. But he did not despair. He at once began to rally German science, saying that without an army and without colonies, and bearing the burden of reparations, Germany would need science more than ever. He was one of the most active founders of the Society for Protecting German Science, which held research institutions and scientists together through the period of inflation and reconstruction.

He even investigated the possibility of recovering gold from the sea, as a means of meeting the reparations. His love of the Fatherland persisted as strongly as ever. He began a speech to the German Club in Buenos Aires in 1923 with the words "Nothing is more precious, when far away in a strange part of the earth, than to find once more the mother tongue and the mode of thought of the homeland." He told his hearers that they, who, after the downfall of Germany, had stood up for her in a strange land, were permitted to adopt as a motto the great saying of Fichte, "To be German is to have character," and he thanked them for their gifts to "German youth and German science, which together make the German future."

Haber was the greatest authority of his time on the relations between chemistry and industry, and he was fond of the theme. He liked to discourse on the explanations of the difference between the history of chemical industry in Germany and in other countries. He remarked that chemical industry began in England, and arose out of the industrial revolution. This created a new demand for chemicals. Where formerly they had been required in small quantities for dyeing and other small-scale industries conducted in the home, they were now required by the ton for treating the products of the recently developed factories. The early English industrialists discovered how to produce the required quantities of chemicals by empirical methods, and sold them with great profit. Their profits were so great that they had not much stimulus

to discover economical, that is, scientific, methods of working. They became rich and accumulated large reserves. They dominated the markets for years, and their wealth hindered competition from new firms. As the years passed, they did not fail to discover many tricks of chemical manufacture through chance events in the factory. So, by 1860, English chemical manufacturers had become wealthy and experienced. As their position seemed so commanding, they saw no reason for modifying their methods. Certainly many of their chemical processes were rather obscure, but they were very profitable, so why improve them?

About this time, German academic chemists began to go to England to work as operatives in the chemical factories. They carefully learned the practical English methods and then returned to Germany, where they started firms of their own. But as they were trained chemists, they succeeded in making small improvements in the English technique. The new German firms soon became famous for quality, and their business rapidly expanded. As the directors of the firms were chemists, they appreciated their clients' difficulties, and tried to solve them and obtain their custom. The English directors were business men. They knew how to drive hard bargains but had not the scientist's mental suppleness in approaching new requirements and solving the problems created by new demands. After enjoying a position of extraordinary strength, they saw their business slip away to German firms. They could not counter it. Not being scientists, they did not know how to handle scientists. They thought that the scientific chemist could be kept entirely subordinate to the business management. The tradition died very hard. But in Germany, where chemical industry had been created by men who were chemists first and business men afterwards, the division never existed in a comparable degree.

The development was characteristic of German industry. Germany was not an industrial nation until the middle of the

nineteenth century. Her industries were created by scientists and leaders, and were not the outcome of an unconscious evolution, as in England. Liebig was a nobleman and a chemist, and he created the manufacture of chemical fertilizers. Von Welsbach exploited the chemical properties of the rare earths, and created the gas-mantle industry, and built a large private laboratory for himself in an old castle. Siemens was a physicist and an electrical engineer, and was the founder of a firm that employed at one time 130,000 operatives.

Haber was of the opinion that the English social system hindered the growth of a fertile relation between industrialist and scientist. The social aim of both of them was to be leisured gentlemen. Consequently, whenever they met on social occasions, or in their club, the last subjects they discussed were business and chemistry. "Shop" was taboo. This was not the tradition in Germany. There the business man was expected to talk about business, and the scientist about science. He believed that a similar situation existed in America, and this helped to explain why scientists often received such large endowments from American business men.

H. Levinstein suggested in his Perkin Memorial Lecture of 1938 that the decline of the English chemical industry in the latter half of the nineteenth century might have been due to social causes. He said that it was not due to the chemists or technologists, nor even perhaps to the salesmen or the direction. "Perhaps it was more our social system. Certainly chemists had very little standing, but in general business was looked down on and was not encouraged or rewarded as it was in Germany. The Kaiser would call in quite informally in passing to see one of the great works. Here in England a man would retire when he had made enough money to live in the country, to be a sportsman, to shoot birds with skill, or to hunt foxes with resolution. It was a quicker route to social success."

The superior development of chemistry in Germany was due, in Haber's opinion, to two sources: the better manage-

ment of research, and the superior inner structure of industry, in which business man, technologist and chemist collaborated on a more equal footing than elsewhere. The first source arose from the tradition of training in the universities. Chemists of genius were not more common in Germany than elsewhere, but when they appeared, they became professors, and spent far more energy than the French and English chemists of genius in training a body of men who, though without genius, were capable of learning. These not only acted as able assistants to them in their own researches, but provided a large reserve from which industry could draw competent technical recruits. The existence of this large reserve of competent men was a decisive factor in the supersession of French and English by German chemistry, for while men of genius could always find a track, the conversion of the track into a smooth highway of progress could be accomplished only by the tramping of a large body of followers.

Haber found the origins of the German system of training research workers in the circumstances of German history. The Germans had learned to think in the school of Kant, and to observe nature through the example of Humboldt. Decades of conscription had taught them how to fit into large organizations, and life on an infertile soil had taught them how to work. The energy with which they adopted modern technology was released through the success of the struggle for national unification, typified by the formation of the Empire in 1871.

Haber continued his guidance of German science after the war in his great institute at Dahlem. It was a fine, light building, cleanly designed and magnificently equipped. It was the best of its kind, and research students went to work there from all parts of the world. They enjoyed not only Haber's inspiration and the resources of his institute but also the body of intellectual life centred in the group of institutes at Dahlem.

Then, in 1933, when the Nazis seized power, Jewish mem-

bers of his institute were immediately persecuted. As he was of Jewish descent himself, he felt he must resign in protest. The man who had done more than any other to enable his country, nearly with success, to resist almost the whole of the world was virtually dismissed and expatriated. It was not the first humiliation that he had received as a Jew. In spite of his great work as chief of the Department of Chemical Warfare, the Imperial Army never gave him higher rank than captain.

He found refuge in the country he had struggled to defeat, and was invited to work in the laboratory of Pope, the Cambridge professor who had been one of the leaders in the English reply to his chemical warfare. He said that Rutherford's laboratory was now the world's chief centre of research, and its presence made Cambridge more attractive to him than any other place of research.

Haber was ill when he arrived in England. He suffered from a weak heart. Shortly after his arrival he was entertained by friends in a restaurant in London, and no doubt he expressed his opinion on affairs in Germany in his customary outspoken manner. He presently received a letter from an eminent former scientific colleague, saying that the German Government had learned that he had expressed disloyal sentiments, and asking him to furnish an explanation. This gave him a great shock.

He left England to rest in the south in January, 1934, and died on the journey at Basle, after a severe heart attack.

Haber's life is a microcosm of German history. The energy, the discipline, the achievement and the collapse, and the combination of great virtues and weaknesses, which were illustrated in his career by the grand synthesis of ammonia and the endearing but comic attempt to pay reparations by extracting gold from the sea.

The destruction of Haber's scientific organization in the institute for physical chemistry at Dahlem and the general shrinkage and decline of the Kaiser-Wilhelm-Gesellschaft

also show the dependence of science on social conditions, and the illusory nature of the principle that research may be pursued in independence of them. Science does become an organism with a degree of autonomy, whose growth is stimulated in part through its own internal mechanism of development, but it cannot pursue a life independent of social conditions. It is like a powerful limb on the body of society, which to some extent possesses its own life and growth and can accomplish many things, but it is not an independent organism, and dies when the social body that supports it is diseased.

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THE SOCIAL BACKGROUND OF GERMAN SCIENCE

The most illuminating analysis of the rise of German science and technology has, perhaps, been given by Veblen. He has argued that the composition of the populations in Germany, England, Holland, northern France and Scandinavia is biologically uniform, so no explanation of its features is due to peculiar biological characters. All of these peoples sprang from the populations who lived on the shores of the Baltic and the North Sea in neolithic times. The prehistoric evidence, he thought, seems to show that these peoples lived in small peaceable agricultural communities, whose social acts were governed by assemblies of a majority of their members. Kings and leaders had only a loose control over the communities to which they belonged, and the members were relatively free and anarchistic. They borrowed techniques very freely from southern and eastern sources, but were able to improve on them, as has been shown by the tools that have survived. Veblen believed that the neolithic activities of the Baltic peoples were the most natural expression of their biological aptitudes, as the neolithic was the only period through which they had lived that was long enough for biological selection to have had some effect in giving them definite biological characters. He thought that the descendants of these peoples—the Germans, English, northern French, etc.—would always tend, if circumstances permitted, to an anarchistic or democratic society resembling the neolithic.

The present English and German peoples were founded by

marauders from the Baltic and North Sea coasts. These consisted of groups who were unable to find a comfortable living in the expanding communities at home. The neolithic tradition of freedom within the community was still too strong to allow such dissatisfied chiefs to become hereditary kings, so they sought power abroad. Those who sailed overseas came to England and conquered peoples who had long been governed by Romans and Churchmen, and they soon acquired some elements of their civilization and peaceableness. Those who wandered away from the coasts came to Germany, where they conquered a barbarian population from whom they had nothing to learn, and they established themselves there as predatory chiefs.

These chiefs adopted Christianity some six centuries later, when their predatory tradition was already ancient and firmly established. After the adoption of their new creed they invaded Prussia. Thus Prussia became the newest part of Germany, with a fresh and strong predatory tradition. This tradition was still strong in Prussia when it was declining in countries with older social systems, such as England and France.

The contrast between the descendants of the Germanic peoples in England and in Prussia had become marked by the beginning of the sixteenth century. Those in England were beginning to enjoy the safety of her island isolation, and were already reverting to the habits of freedom and technological borrowing of their Baltic neolithic ancestors. Those on the defenceless plains of Prussia were still as predatory and dynastic as ever, through their continual fighting with Slav neighbours.

The English technical borrowings in the Elizabethan period diverted interest to technology during a time when the nation could not engage in big offensive wars. As technology involves the study of impersonal forces, it tends to undermine respect for personal domination, so the Elizabethan imperi-

alism that imported the technology was itself undermined by it. In the next century, the triumph of the new spirit was signified by the execution of Charles I and the deposition of James II, and the establishment of government for the service of trade and not of personal domination.

During the next two centuries, the English, with their partial reversion to the initiative of neolithic anarchism through continuous national safety and their establishment of a business society, were able to carry out the industrial revolution, creating modern technology and science as by-product.

Prussia and the German principalities were still substantially feudal at the beginning of the nineteenth century. Their productive system was still based on handicraft, and they were now beginning to feel the pressure of English economic supremacy severely. It was evident that Germany must unite, or she would be economically exploited by the more progressive society.

The threat of economic subjection made the German principalities unite. This was carried out under the leadership of Prussia. As she still had a feudal social structure, she accomplished this unification by feudal methods. She dominated the whole of Germany, and confirmed her leadership by successful wars, culminating in 1871.

Germany, with her feudal unity, now decided to acquire the technique laboriously worked out in England during two centuries. Technically, she had a fairly clean sheet. She could choose the methods that time had revealed as the best. Owing to the principle of domination, the population could be ordered to adopt these at once.

The adoption presented few difficulties. The fundamental ideas had been worked out. Feudal Germany was not short of trained scholars. Veblen was of the opinion that this was owing to the poverty of German feudal society. In England, men proved their social status by racing and sport. In Germany they could not afford this, so they acquired learning, which is

the cheapest way of acquiring social prestige. They naturally applied their trained minds to meditation on the notions of feudal society and the ideas of personal relationship. They evolved the typical German philosophical systems from this set of ideas.

Veblen believed that German philosophy has no fundamental connection with science or with an industrial society, and has value only to those who accept the values of feudalism. He was careful to add that he did not suggest that industrialism was necessarily better than feudalism, or that modern science is better than classical German philosophy, but he contended that they must be assessed by different scales of value.

The new German industrialists had a large reserve of former philosophers accustomed to a very thrifty life. They made excellent managers, and ran industry more efficiently than the English, whose system was already old and hampered with obsolescence.

The German workmen were literate and quickly learned machine methods, which were simpler than the handicrafts they had formerly practised. As members of a feudal state, they understood how to obey orders, for they had not, like English workmen, become troublesome by reverting to the free and lazy habits of their Baltic ancestors.

The industrialization of Germany advanced with tremendous success. The power of her society, with its feudal traditions, was correspondingly increased, and sought expansion. It came into collision with that of England, with her older industrial society. America and France, whose social forms are closer to England's, sided with her, and the expansion of Germany was temporarily halted. The feudal tradition did not die, and the rationalization of industry was continued, with a corresponding development of science of unparalleled magnitude. In 1933, four years after Veblen's death, the feudal German state recovered its normal mode of leadership and, in 1939, again attacked England and France.

Veblen forecast in 1915 that Germany must remain un-

stable as long as she attempted to combine a feudal social tradition with scientific industrialism. These are essentially antagonistic, and though feudalistic authoritarianism can learn technique quickly through its command of force, it is improbable that it will discover anything fundamentally new in science. Germany has not created modern science. She has only extended it, and it is not probable that she will invent the fundamentally new science of the future, because this will not be conceivable in terms of the sort of thought fostered in a society organized by personal domination.

He thought that Germany might subside into a second-rate power or might liquidate her feudalism, but she also might conquer the world, and that then society might decline to a lower level of civilization "by recourse to so drastic a reaction in their civil and political institutions as will offset, presently neutralize, and eventually dispel the effects wrought by habituation to the ways and means of modern industry and the exact sciences."

Veblen pointed out that the spread of pacifism in the interest of trade, and the decline of the prestige of social status in industrial society through attention to matter instead of persons, did not form a certain foundation for peace and democracy. "Temperamentally erratic individuals, however, and such as are schooled by special class tradition or predisposed by special class interest, will readily see the merits of warlike enterprise and keep alive the tradition of national animosity. Patriotism, piracy and prerogative converge to a common issue. Where it happens that an individual gifted with an extravagant congenital bias of this character is at the same time exposed to circumstances favouring the development of a truculent megalomania and is placed in such a position of irresponsible authority and authentic prerogative as will lend countenance to his idiosyncrasies, his bent may easily gather vogue, become fashionable, and with due persistence and shrewd management come so ubiquitously into habitual ac-

ceptance as in effect to throw the population at large into an enthusiastically bellicose frame of mind. Such is particularly apt to be the consequence in the case of a people whose historical traditions run in terms of dynastic strategy and whose workaday scheme of institutions is drawn on lines of coercion, prerogative and loyalty."

The incidents of Haber's career illustrate the uneasy combination of feudalistic modes of thought with modern scientific ideas which exists in German civilization, and how, after the most tremendous achievements, it is liable to sudden breakdown.

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PERSONAL MOTIVES FOR RESEARCH

The personal motives that direct scientists to engage in research are of at least five sorts. The one which is best known, and most frequently announced by scientists themselves, is curiosity, or the desire for understanding for its own sake. Another very powerful and general motive is the desire for reputation. A third is the need to earn a living. A fourth is the desire to enjoy oneself. A fifth is the desire to serve humanity. Very little psychological research has been done to discover the relative weight of these motives in practice.

The classical view that discovery is primarily due to the motivation of pure curiosity has been admirably restated by Polanyi in his review of J. D. Bernal's book on the Social Function of Science. He believes that science is in the first place a body of valid ideas. It consists of autonomous branches, such as mathematics, physics, chemistry and biology. Each new addition to them is produced by methods characteristic for each branch and is incorporated only after it has been accepted by recognized experts. The various branches of science are thus independent organisms of ideas, which grow with a life of their own. Polanyi contends that these systems of ideas are the most permanent human creations. The science of Mesopotamia, Egypt and Europe has survived, while creeds and laws, and even crafts, have been forgotten. "It seems that an ordered framework of ideas in which each single part is borne out by the cohesion of the whole is of supreme attraction to the human mind. Struggling for a foothold in a shifting world, the mind clings persistently to these rare structures of

sound and consistent ideas. It is in these structures, accordingly, that all scientific interest resides." Polanyi follows Bernal in quoting T. H. Huxley's statement that that which stirs the pulses of scientists "is the love of knowledge and the joy of discovery of the causes of things sung by the old poet—the supreme delight of extending the realms of law and order ever farther towards the unattainable goals of the infinitely great and the infinitely small, between which our little race of life is run." Sometimes the scientist lights on something of practical value. Those who are benefited rejoice, but "even while the cries of jubilation resound and this flotsam and jetsam of the tide of investigation is being turned into the wages of workmen and the wealth of capitalists, the crest of the wave of scientific investigation is far away on its course over the illimitable oceans of the unknown."

In view of these statements it will be useful to see what motives for research are implied by the behaviour and accounts of some other scientists. Those in whom the motive to understand and to construct a coherent system of ideas that will explain phenomena is very strong often publish their results reluctantly or not at all. Newton, Cavendish and Darwin were striking examples. Before Newton published his first paper he wrote in a letter to Collins, which contained the solution of a problem in annuities: "You have my leave to insert it into the Philosophical Transactions, so it be without my name to it. For I see not what there is desirable in public esteem, were I able to acquire and maintain it. It would perhaps increase my acquaintance, the thing which I chiefly study to decline."

He "designed to suppress" the third book of the *Principia*, because "philosophy is such an impertinently litigious Lady, that a man had as good be engaged in lawsuits, as have to do with her."

Cavendish invented electrical condensers, and discovered and measured specific inductive capacity with them. This work remained unpublished and its results were rediscovered

by Faraday. Cavendish "studied to decline increasing his acquaintance" by having his meals placed through a hole in the wall of his room, so that he need not speak to anyone and interruptions be reduced to a minimum. Darwin worked on the material of the *Origin of Species* for more than twenty years, and might never have prepared it for publication without pressure from Lyell. This sort of behaviour is best explained by the existence of the desire to understand as a motive for research.

Scientists have generally not been so explicit in acknowledging the motive of desire for reputation. But it is implicit in the behaviour of many, and especially in some of those who deny it. Newton himself, whose behaviour showed such strong marks of the motive of the desire to understand, dropped scientific research as soon as he had acquired social position through his scientific reputation. He had been elected Member of Parliament for Cambridge University, which brought him in contact with men of affairs. He then conceived an intense desire for a higher social position. He assiduously pressed Locke to use his influence with statesmen to find him a place, and when at first Locke did not succeed, he lamented that the philosopher, as L. T. More says, "would not care to visit such an unsuccessful place-hunter as himself, and if the Monmouths now forsook him, there would be no hope left; and he must reconcile himself to end his days in the obscurity of an academic life. Lest he may have hurt this last chance, he apologized with almost abject humility for what may have seemed to be an intrusion upon the nobleman's society."

Disputes over priority are one of the strongest proofs of desire for reputation. Newton was engaged in several, and Charles Darwin wrote that though he "hated the idea of writing for priority," he would be "vexed if anyone were to publish my doctrines before me."

One of the rare accounts by a scientist of his mode of work

is Blackett's essay on the *Craft of Experimental Physics.* He says that the experimental physicist has "changed the technique of living by his intense curiosity to find out about obscure things." He is a "Jack-of-All-Trades, a versatile but amateur craftsman." He must be able to blow glass, turn metal, carpenter, photograph, wire electric circuits, and be a master of gadgets, though he would not be sufficiently expert in any one of these things to earn his living by it. He has to do these things for three-quarters of his working day. He must "be enough of a theorist to know what experiments are worth doing and enough of a craftsman to be able to do them." His "choice of subject will often be mainly determined by his special aptitudes," as to whether he is a glass-blower or engineer. In English laboratories he tends to depend on his own resources in making apparatus, and there is perhaps a relation between this tradition and the vogue of practical hobbies. "So perhaps English experimental physics has derived strength from the social tradition and moral principles which led the growing middle class to spend the leisure of its prosperity in the home rather than the café."

Experimental discovery depends on the utilization to their limit of the properties of available materials. Much of an experimenter's time is devoted to "overcoming these limitations." The progress of technique "is continually opening up the possibility of new fields of research," and "the development of theoretical physics both suggests new fields of enquiry and brings new relevance to old ones." But "the experimenter is always a specialist and does not often change his technique to follow the latest theoretical fashion. Often he cannot usefully do so, for there are few experiments which do not need a considerable apprenticeship."

The experimenter gains knowledge of machinery and moving objects in "this mechanical and ball-playing age." The experimenter acquires an intuitive knowledge that assists him

to guess how processes work. It is "a very complicated process involving a combination of abstract thinking with the use of visual and motor imagery."

"With such varied manual and mental skills as have been described does the experimenter go about his work in the laboratory, an amateur in each alone, but unique in commanding them all.

"It is the intimate relation between these activities of hand and mind which gives to the craft of the experimenter its peculiar charm. It is difficult to find in other professions such a happy mixture of both activities. Few people are content with an occupation whose only manual element is the handling of a pen or a typewriter. Yet many, who embark on the career of an engineer from love of using tools, find later on that their main activity is as sedentary as that of a bank clerk. A common reaction to the fact that the office worker is, with some notable exceptions, paid more than the skilled mechanic, is to embrace, when possible, the career of the former while adopting some practical hobby to offset the loss of the satisfaction to be derived from the latter. The experimental scientist is luckier; his legitimate field of activity ranges from carpentering to mechanics; it is his job both to make and to think, and he can divide his time as he thinks fit between both these pleasurable occupations."

This account of the experimental physicist's activities gives a very strong impression of one of his chief motives. It is a desire for a legitimate excuse to engage in enjoyable tinkering. There is no hint in it of that search for certainties in a world of flux mentioned by Polanyi and T. H. Huxley.

It is difficult, if not impossible, to find any expressions in the works of Newton, Cavendish and Darwin which express or imply this desire. These men were engaged in the less altruistic activity of finding pleasure in the exercise of their special aptitudes. This explains why they were rather selfishly reluc-

tant to publish. They all possessed intense curiosity, but the pyramids of fact and theory that they built were the result of a magpie or acquisitive curiosity rather than a desire to discover new knowledge of man's destiny.

The view that has been expressed so eloquently by T. H. Huxley and Polanyi is in fact more characteristic of the propagandist than the research worker. Some light on Huxley's mind and motives may be gained by comparing his diary of the voyage on the *Rattlesnake* with Darwin's diary of the voyage on the *Beagle*. Both were written when their authors were twenty-five, under similar conditions in the most formative years. They present an illuminating contrast of the differences in mind between men who were to become the greatest propagandist and the greatest research worker of their generation. There is scarcely one reflection or sign of interest in scientific matters in Huxley's book. He is concerned primarily with personal psychological problems and resistance to fits of depression. Darwin's book, in spite of his bad health, is devoted from the beginning to the collection of facts and the development of scientific ideas.

It is evident that Darwin proceeded to exercise his tremendous aptitude for collecting and resuming facts without reflecting much on the value of his activity.

The stirring reflections of Huxley on man's place in nature have their root in his personal psychological problems, and they deal with the implications of the results of research rather than with the motives that prompted it.

Curiosity is not in itself, or in its processes, particularly noble. Various animals possess it, and it is apt to lead to trivial activities. It is often associated with acquisitiveness and, in this combination, has led especially to the accumulation of a large part of biological science. As a psychological process, it is a sublimation of the desire for power. The curious person wishes to discover the knowledge that will place a phenomenon under his control, either in fact or in understanding. His feeling

of triumph when he has made a discovery is a feeling of triumph over something; he has brought some aspect of nature under his power.

The psychology of discovery is in all circumstances substantially the same. The scientist working in his own home, or in a university research laboratory, is in virtually the same psychological condition in all of these institutions during the moment or period of discovery. In his own home, or if he is a senior professor, he may tell himself to attempt to elucidate some as yet unexplained phenomenon; if he is working in an industrial research laboratory, particular problems will be chosen for him. In the first instances, he appears to choose his problem of his own violition, while in the second he is definitely aware that it has been suggested to him by persons who form part of his environment. These circumstances help to explain the difference between pure and applied science. A scientist feels he is engaged in pure science when he is not conscious of motives other than his own volition and the internal logic of development of the problem with which he is concerned. The latter is in his own mind, and appears to him to be independent of the environment and the external world.

A scientist feels he is engaged in applied science when he is strongly conscious of the external influences that have directed his choice of investigation.

The scientist who makes important discoveries usually does it at the expense of severe concentration. Difficult problems are solved only by the most intense mental focussing, and as a result the research scientist is apt to become unconscious of all the objective conditions that have influenced his research. This circumstance provides the basis for the view that "all scientists are anarchists at heart." If objective conditions that have influenced his research are subtle and obscure, he may forget, or never be conscious of, their existence. This is the condition of the majority of scientists engaged in academic research laboratories. The intense concentration that fre-

quently inhibits the awareness of scientists to social relations is also the cause of the traditional absent-mindedness of professors.

But those who work in industrial research laboratories cannot forget the objective conditions for long, though even they forget them in the periods of mental concentration during actual discovery. If the industrial research scientist could be asked during his moment of concentration how he has solved his problem, he will say that he has done it by following its internal logic. This is true, but it is also quite clear that he would never have solved it unless his attention had been directed to it by external influences.

The view that science is an independent system of ideas is a product of subjectivism. It springs from the same motives as Plato's philosophy. Some comments on the nature and fate of this philosophy have been made in an earlier section. Plato advocated the dictatorship of the intellectual, and was the first to give a sketch of the philosophy of Fascism. His representation of science as an organism of ideas independent of the material world appears to be disinterested, but in fact it concealed political ambition. He identified these ideas with truth, and concluded that as only intellectuals could deal with ideas, only they were acquainted with truth, and therefore only they deserved political power.

The desire to follow the internal logic of systems of ideas is more philosophical than scientific. It is seen very strongly in German philosophy. When a German student was asked "What is the point of Fichte's philosophy?" he was quite nonplussed. He could not understand what was meant. He was then asked why he studied Fichte. After some thought he answered, "Because it is interesting to see how he deduces one thing from another." This is not the essence of scientific activity. Clerk Maxwell expressed it clearly when he said that it consisted in "wrenching the mind away from the symbols to the objects and from the objects back to the symbols." It

is an interaction between the internal and external worlds. Of these, the priority of the external world is a historical fact.

The motive of desire for reputation is much stronger than is generally admitted. The output of research by many scientists declines after they have secured election to distinguished societies, or after they have been appointed senior professors or directors of institutions. Scientists primarily interested in research can nearly always use the power given by senior positions to extend the scope of their researches. They can organize their staff as a team. But many do not do this, under the excuse that their administrative duties are too exacting. It is hardly necessary to mention the aspiration for titles sometimes seen in scientists whose work is world famous.

C. P. Snow has given interesting sketches of the influence on scientists of the motive of reputation in his novel, *The Search.*

The simple motive of earning a living is also underrated. The need for bread and lodging is the motive of far more research than is commonly realized. A man with aptitude for research can often earn his living more easily through that aptitude than in any other way. It is said that he could easily earn more in other professions if he cared to enter them. The number of cases in which this is true is probably exaggerated. The absence of the best conditions for research does not necessarily drive a gifted man into another profession where he can do good work; it often means that he can do no creative work at all. He may become a garage mechanic or a library assistant. The National Union of Scientific Workers were of the opinion that the provision of "such material comfort as is necessary for a well-developed life, and for such luxuries as are usual in the society which the worker frequents" would be a strong stimulus to research, and that this could be made most satisfactorily by paying scientists salaries at rates and in conditions similar to those of the Civil Service.

The fifth of the motives under consideration is the desire to serve humanity. Bernal has stated that "men require that what they do has social importance" besides satisfying their own curiosity and enjoyment. Polanyi complains that he rejects "any claim of science to be pursued merely for the sake of discovering truth." No analysis has been made of the size of the contributions to science due respectively to the personal motives of discovering truth, acquiring reputation and power, seeking enjoyment, gaining a living, or serving humanity. One might as well guess that each has contributed equally.

At any rate, it is certain that the last motive has made a large contribution, and historical research may subsequently prove that it is the largest of all. The progress of humanity, which is always positive when the periods considered are sufficiently long, is a proof that mankind in the long run encourages those things of benefit to itself. Much has been mentioned in earlier sections which indicates how strongly the desire to serve humanity has assisted the development of science. It is sufficient to recall the tremendous inspiration of Bacon, due mainly to that motive, and how it contributed, through Boyle, Sprat and their colleagues, to the formation of the Royal Society and all that that implied for the advancement of science.

Benjamin Franklin owed much of his inspiration to that desire. When he founded the American Philosophical Society he proposed a long list of subjects for research, which were to include "all philosophical experiments that let light into the nature of things, tend to increase the power of man over matter and multiply the conveniences or pleasures of life."

Franklin refused to seek patents for his inventions, so that they should freely benefit all men. Davy refused to patent the safety lamp because his "sole object was to serve the cause of humanity."

The Royal Institution, where Davy worked and which has contributed so much to scientific research, was founded

"for diffusing the knowledge and facilitating the general and speedy introduction of new and useful mechanical inventions and improvements; and also for teaching, by regular courses of philosophical lectures and experiments, the applications of the new discoveries in science to the improvement of arts and manufactures, and in facilitating the means of procuring the comforts and conveniences of life."

"A good cook was engaged for the improvement of culinary advancement—one object, and not the least important—for the Royal Institution."

Researches on improved recipes for soup, which were to give the maximum nutriment at the minimum price; more economical fire-grades, etc., were conducted for the benefit of the poor.

Some years later, in Paris, Pasteur was making researches which owed much to the inspiration of the social motive. He passionately desired to save diseased men, animals and plants, and he helped to demonstrate that the cultivation of science was one of the best ways of achieving this. He wrote that "in our century science is the soul of the prosperity of nations and the living source of all progress. Undoubtedly the tiring discussions of politics seem to be our guide—empty appearances. What really leads us forward is a few scientific discoveries and their application." One can recognize the social motive in this, without agreeing with all that he says.

A large part of medical research has been done chiefly from the social motive. Numbers of medical research workers have died while submitting themselves to experiments. The Americans who died in the elucidation of yellow fever are distinguished examples.

Those who have furnished the means that have enabled scientists to make discoveries have assisted science through their personal desire to serve humanity. The founder of the Rockefeller Foundation, with its aim of promoting "the Well-being

of Mankind throughout the World," was no doubt moved by several motives, but one of these was the desire to help humanity.

The justification of the cultivation of science because it adds to a fascinating organism of ideas, or to the discovery of pure truth, seems a little cold, mean and selfish when compared with the motives that inspired Bacon and his successors. The progress of science has owed much to the desire to serve humanity, and it is probable that in the future, through better organization of the expression of this motive, the progress of science will owe more to it than to any other personal motive.

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EXTERNAL MOTIVES OF RESEARCH: THE EXPANSION OF BUSINESS

The reasons why industrial firms are creating research laboratories have been explained particularly clearly by F. B. Jewett, the president of the Bell Telephone Laboratories. He said that the research workers in any industrial concern are motivated by the same considerations and are governed by the same rules as those that apply to other groups in the organization. The primary difference between them and those engaged in operation, finance, purchasing and selling is in training. They are skilled in the facts and methods of science rather than in the techniques required in the other branches.

The successful industrial research organization must operate as an integral part of the industry.

The systematic creation of industrial research laboratories began about 1900. It arose from the exhaustion of the method of improvement used by the engineers who had invented the steam engine and founded the industrial revolution. The great achievements of these men rested on their rough grasp of scientific methods, which had gradually been discovered since the Renaissance, and indicated that there was a positive best way of dealing with new things, and that this led to improvements more quickly than innumerable and uncorrelated experiments. But the pioneers had relatively little understanding of the finer points of the fundamental sciences that underlay their practice. When their accumulation of knowledge had been pretty well worked over by the cruder methods, "the recovery of the hidden values" required the introduction into

industry of men who understood the basic facts of science and the methods by which they are obtained.

Different industries began to establish research laboratories at different dates, because this situation concerning technical knowledge arises in different industries at different dates.

Jewett compares the introduction of industrial research with the introduction of finer techniques in the mining of gold as lodes become poorer and less accessible. At first, the gold is gained by two or three men with the washing pan. Then it is ground out of the rock by hydraulic mills, which required engineering supervision. Finally, good returns from the remaining poorer lodes are possible only by the cyanide and other refined processes. Through these, skilled men with a training of a type entirely different from that of their predecessors are drawn into the industry.

This situation arose in the electrical-communications industry about 1900. It became evident that "the recovery of further values from science, which we knew to exist," could not be obtained by men whose knowledge was restricted to what they had learned at college and had since acquired by experience. Such men, who knew little of "the fundamentals of science itself," found themselves impotent to produce in the electrical field the advances that were obviously potentially at hand. "In our particular industry it became evident quite rapidly that we had to introduce men of a different type of training, if we were going to continue to progress."

The investigators in the universities were advancing physical and chemical knowledge at an enormous rate, and provided a "great array of new and as yet unapplied material."

These could be utilized in industry only by men who "knew as much about the new things and the methods of their production and manipulation as the scientists who were their discoverers." Consequently, the juxtaposition of "the obstacles to further progress along old lines and the assemblage of new facts on which progress could be made," was the cause

of the foundation of the first great research laboratory in the electrical industry.

The research laboratory in industrial organization has become not only the source of continued progress, but a bulwark against the vicissitudes of hard times. Experience has shown that progress may be made most rapidly, cheaply, with the smallest number of missteps in the laboratory. They have found this to be the case, not only in times of expanding business, when there were urgent demands for new things and production on a larger and more economical scale, but also in periods of depression, when further economy in standard processes and the "development of new things for which a demand can be created" became more pressing.

Jewett says that in 1931, when American trade was very bad, his organization was doing everything it could to keep its trained research personnel, and transfer them from "problems of an expanding business period to the type of problems which will most directly benefit our situation in these depressed times or most surely benefit us in the years ahead, when, as we all hope, the sun of prosperity will again be shining."

The preliminary training of industrial research staff is long and arduous, and the period of time required "to mould wholly efficient men into an efficient team is long." It is therefore impossible to contemplate the sort of ups and downs in the research part that may be regarded with equanimity in other parts of a business.

The industrial research laboratory has a relation to the rest of an industrial organization which resembles that of a gland to the body. The size and expenditure is less than in many other departments, but without it, vigorous life would soon cease. The importance of research had been recognized in the electrical-communications industry by the appointment of its directors as members of the controlling executive management.

Jewett complains that there has been much foolish talk from persons who should know better to the effect that research laboratories are places provided by industry in which trained scientists "are free to do whatever they please on any kind of a problem that happens to strike their fancy." This picture has done great harm. As the research laboratory is part of an industrial organization, it "must of necessity be guided by the conditions governing the particular industry of which it is a part." Except for a little transient advertising value, there is "little real worth in any industrial group which does not concern itself primarily and practically exclusively with the problem of its own industry or with the fields into which that industry may legitimately and logically expand its operations."

In times of flush and lavish prosperity, a management might delude itself into believing that expenditure on research unco-ordinated with their business might enhance its prestige as a great, progressive, far-seeing group of men. But when the cold wind of adversity begins to blow, this exotic flower would shrivel up with extreme rapidity.

And yet, in his own research organization, they have men who investigate problems that have no practical relations to the business. One reason why these researches are tolerated is that they are regarded as avocations, similar to those of men in other departments. "We do not hire scientific men to do the extraneous things, nor do we ask them to do them after they are hired." If, however, they are inclined to investigate problems foreign to the business, no obstacles are placed in their way as long as they "continue to be of value as cultivators of our field." In fact, within limits, they further their avocational desires because this allows fuller exercise of creative ability, which is the chief source of happiness to the scientist, and it is recognized that the best work is obtained from the men who are most happy in their environment. They do not put rigid iron clamps on men and say, "You must do this kind of research work to the total exclusion of all other kinds of research

work." This would defeat its own ends by killing creative ability, or causing the man to leave the organization.

They have in their laboratories a number of scientists who have made researches that are famous outside the field of telephony. These are, however, amongst the most valuable men in the organization because of their deep knowledge of other problems bearing principle concern of the business.

These men have been trained in the business, so, though they may spend a considerable part of their time on matters far removed from telephony, they are able to recognize recondite information which may be of assistance to it, and in some instances, owing to their own original researches, they are the sole persons aware of the existence of this information. But if these scientists should lose interest in the major problems of telephony and devote themselves exclusively to foreign fields of research, "there would be no justification for our maintaining them on the pay roll."

Industrial research is not undertaken primarily to secure patents. It would continue even if patents as a form of property of limited life were abolished. "Practically all organized industrial research is undertaken for the purpose of solving problems thought to be of benefit to the industry."

It is of great assistance in the development of large-scale processes. Large sums have been wasted on attempting to proceed directly from theoretical conceptions to large-scale production. In many cases the attempt failed, and it was concluded that the theoretical conceptions were wrong and unworkable, whereas the failure was due to ignorance of control and operational methods, which could have been removed by preliminary experimental research. Owing to their success in solving problems and creating new demands, research methods have gradually spread to the manufacturing and operating departments of the business, and this has been accompanied by the transfer of men trained in research into these departments, where they have shown that systematic study is more profita-

ble than "cut-and-dried" methods in eliminating difficulties.

It is certain that industrial research laboratories will extend, and will arise in industries where they do not exist. This is due to the avalanche of new facts coming from the laboratories for fundamental research. Much of this has an obvious bearing on existing industries, and much presages the possibility of new industries. As much of the new knowledge concerns the ultimate structure of matter and the laws that it obeys, it can be utilized only by research men, as they only are the persons who understand it. One can forecast that industrial research workers will need a still more highly specialized training in this knowledge in order to find how it may be utilized.

Jewett considers that "modern science in all its forms had birth" in colleges and universities. Its utilization has made much industrial work more interesting, though, "to be sure, it enlarged things more, possibly, on the material side by opening up hitherto unsuspected regions where the forces of nature were at play than it did on the more directly human side."

Jewett states that in 1914 the improvement of telephone equipment had come virtually to an end. They had advanced for forty years by steadily improving the design of instruments, many of whose parts were made of magnetic materials. These were purchased in the market. They were the best available, and their properties were utilized to the best advantage by careful refinements in the design of the instruments in which they were used. The performances of these instruments were definitely limited by the range of properties in their magnetic parts. But it was known on theoretical ground that instruments giving far higher performance could be made if materials with a different range of magnetic properties could be produced. The telephone industry had been buying its irons and steels from manufacturers who produced them for other purposes. Was it possible that magnetic ma-

terials with the desired properties could be made? The search was planned and begun. Existing knowledge of magnetic materials was scrutinized, and the properties of metals that might be used in magnetic alloys were investigated. After lengthy researches a simple alloy of iron and nickel was found which, when prepared under rigidly controlled conditions, had magnetic properties many times greater than the materials previously used in telephone and telegraph instruments. It was given the name "permalloy."

Its first application was unexpected. For nearly sixty years, the speed of transmission of submarine cables had remained virtually constant, though it was known theoretically that the association of magnetic material with the conducting wire might increase it. Many attempts to apply this knowledge were made, but failed. Then, after the discovery of permalloy, research was started to see whether it might be applied to this purpose. It was found that if very thin strips were coiled around the conducting wire, an enormous increase in speed of transmission could be obtained. The amount of permalloy needed, and the cost of the additional process in manufacture, was not great, but six or more times as many messages could be sent on one of the new cables than on an old one of the same size.

Before the discovery of permalloy, the limit of telephonic communication was about one thousand miles. Chiefly through its aid, and that of another consciously sought implement—the vacuum tube amplifier—transcontinental telephony became possible.

The amplifier was required to strengthen the effects of very weak and attenuated voice currents without distorting them, so that the message borne by them would be intelligible after travelling several thousand miles. These amplifiers were produced through intense coordinated research on the properties of ions and electrons, by men with the finest training and the best tools that could be obtained. They were first used on a

large scale in long-distance telephone cables, but they provided the basis of the modern loud-speaker, which was first used for magnifying the voice of speakers to large audiences, and antedated the radio and the talking films.

The effects of these advances have been described by Jewett: "A great industry once powerful and prosperous, threatened with decay and dissolution through lack of change and advancement, revivified overnight—its figures on the red side of the ledger changed, as if by magic, to larger and more imposing black figures; organizations which seemed stable as the eternal hills, shaken to their foundations and forced to revamp their entire business structure as well as their outlook on the future; other businesses struggling to eke out a bare livelihood, suddenly raised to the pinnacles of opulence; professions learned through hard and dreary years, thrown into the limbo of the unwanted and new professional requirements established; these and more are the direct results of man's desire to use the by-product results which have come from the work of research men seeking to improve a nation's telephone system."

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EXTERNAL MOTIVES OF RESEARCH: NATIONAL SAFETY

The British Government established in 1915 a committee which was the parent of the present Department of Scientific and Industrial Research. The circumstances in which this occurred were described in the introduction to the committee's first report. Its authors state that certain events which preceded the establishment of the committee "are worthy of record because they are now seen to have a general significance which was not realized at the time."

The Imperial Institute had been founded in 1887. Its purpose was to encourage the trades and industries of the British Empire by the provision of exact information on the raw materials and manufactured products yielded by various parts of the Empire. "Knowledge of this kind necessitated careful scientific tests and these in turn revealed the need for research directed to the elucidation of obscure qualities in a product in the interests alike of the producer and of the user."

This movement was extended by the foundation of the National Physical Laboratory in 1902. This had grown out of the work of the British Association's Committee on Standards, which in turn had been formed to assist the new industries of the second half of the nineteenth century, by providing them with accurate methods of measuring and standardizing materials. Until this had been done, the manufacture of very uniform materials, necessary for the industrial technique of mass-production, was not possible.

When King George V, then Prince of Wales, opened the Laboratory, he said that he understood that it was the first

research institution founded by the British State, and its object was "to bring scientific knowledge to bear practically upon our everyday industrial and commercial life, to break down the barrier between theory and practice, to effect a union between science and commerce."

This movement extended slowly until 1914, when the need for accelerating it suddenly became acute. The outbreak of war cut off the imports from Germany of certain products manufactured by highly scientific processes and essential for modern armaments and industry. The existing British industry was unable to make even two dozen of the hundred different sorts of optical glass used in range finders, field glasses and other instruments, hitherto supplied by Germany. It could not supply ten per cent of the dyes needed by the great textile industry, and it was also unable to replace the German exports of drugs, magnetos and tungsten, or even the zinc smelted in Germany from ores mined in parts of the British Empire.

It was evident that the movement for cooperation between science and industry, which had been slowly growing, required rapid acceleration. "Other machinery and additional State assistance were absolutely necessary . . . but it needed the shock of the great war to make the need manifest."

The State had recognized the necessity of organizing the national brain power in the interests of the nation during the normal times of peace by creating the education system. "The necessity for the central control of our machinery for war had been obvious for centuries, but the essential unity of the knowledge which supports both the military and the industrial efforts of the country was not generally understood until the present war revealed it in so many directions as to bring it home to all. War has remained as much an art as ever, but its instruments, originally the work of the craftsman and the artist, are now not only forged by the man of science; they need a scientific training for their effective use. This is equally true of the weapon of industry. The brains, even the very process, that to-

day are necessary to the output of munitions were yesterday needed, and will be needed again tomorrow, for the arts of peace."

It was evident that if the requisite scientific industries were not established, the nation would fail in the war, and if, further, new industrial processes were not discovered, it would fail in the "equally difficult period of reconstruction which will follow the war."

In these circumstances, the Royal Society, and other scientific societies, sent a deputation to the Presidents of the Boards of Trade and Education, to ask for assistance for scientific research. This was granted, and the parent committee of the present Department of Scientific and Industrial Research was formed to work out the best way of administering it.

The committee started a survey to discover how industrialists might be helped by research. The managing director of one big firm told them that he had no interest in research which did not produce results within a year. He wanted a handy servant that would help him to overcome the difficulties that crossed his path day by day, but he did not want a partner with ideas of her own. The chemical industries were so divided that the societies of chemists had neither the influence nor the means to promote much research of value to them. The textile trades were even less advanced. They did not care where dyes and machinery came from as long as profits were satisfactory.

A national register of researches was compiled, but in their first survey they discovered only forty individuals whose work was worthy of assistance.

The research organization of the engineering industry proved to be the most advanced. But in general, "so long as an industry was prosperous it was apt to take short views and feel little enthusiasm for systematic research, especially if the firms it comprised were small, or if the capital engaged had a speculative value on the Stock Exchange."

British firms were only just beginning to realize that their most dangerous competitors were not other British firms, but foreign trusts supported by tariffs. Their tradition of individualism made them suspicious of cooperation, and they did not understand that it "is not the negation of individual effort; it raises initiative to a higher power."

Their failure to cooperate had prevented them from engaging in thorough research, as many had learned from experience that research on the small scale, which individual firms could afford, was unprofitable.

The creation of a satisfactory system of industrial research required the better employment of the nation's scientific ability. England had produced a fair quota of scientists of the first order, but she did not make the best use of those of moderate ability. The intellectual war could not be won by a corps of officers alone, and "without the scientific rank and file it will be as impossible to staff the industrial research laboratories which are coming, as to fight a European war with seven divisions."

The universities were contributing more to science than in 1868, when T. H. Huxley complained that only one in every ten learned books published was written by a professor or academic person, but could still do far more with better laboratories and grants for research expenses and the education of a larger number of students in science.

The authors of the report remarked that "it is not often in our history that the nation has found time to think. Now, by a curious paradox, while the flower of her youth and strength are fighting for her freedom and her life, the others have a chance of thinking out the best use to which that life and freedom can be put when they are safe once more."

The progress of fundamental research and its utilization in industry "will inevitably tend to bring industries into intimate relations, which are at present independent of each other, to transform what have hitherto been crafts into scientific in-

dustries, and to require cooperation not only between different firms in the same industry, but between groups of industries in a continuously widening series of interrelated trades. The forces which are at work in this direction have elsewhere found their expression in connection with the trust and combine, but we believe, if the real nature of these forces is clearly grasped, that it will be possible to organize them for the benefit not only of the industries but of the nation as a whole."

Shortly after the Department of Scientific and Industrial Research was established in England, and plans had been made for corresponding departments in Australia, Canada and elsewhere, the National Academy of Sciences in the United States founded its National Research Council, chiefly from the inspiration of George Ellery Hale. The National Academy itself had been founded in 1863 during the Civil War by Lincoln, and it had been charged, whenever called upon by a government department, to investigate, examine, experiment, and report on any subject of science or art. It gave the government much aid during the Civil War, through its studies of military and industrial problems, and when the engagement of the United States in the war of 1914–18 became imminent, it offered its services again to the government in 1916. A National Research Council was then formed, but on lines different from those of the British Department of Scientific and Industrial Research. It was not a government department, but an independent body consisting of a federation of government, university, private foundation and industrial research agencies. It immediately organized research for military and industrial purposes.

The National Research Council was strongly opposed to the central control of research, but was in favour of cooperative organization. As has been mentioned in the Introduction, Hale, in the first issue of the Council's bulletin, explained that cooperative organization would not hinder original discovery but assist it.

The forces which bring into existence medical research organizations may be illustrated by the origin of the British Medical Research Council. This was established in 1914, in connection with the government's department for National Health Insurance. The National Insurance Act of 1911 contained a provision that one penny for each person insured in the United Kingdom was to be contributed by the government for the endowment of research. A committee was formed in 1913 to administer the fund on research which would extend medical knowledge with the view of increasing the power of preserving health and preventing and combating disease. The biochemist W. M. Fletcher was appointed secretary of this committee in July, 1914. By that date, the fund had accumulated £55,000 in pennies. It founded a national institute of medical research at Mount Vernon, Hampstead. H. H. Dale was appointed to the department of biochemistry and pharmacology, and later became director of the institute. He shared a Nobel Prize in 1936 for researches on the chemical transmission of nervous impulses.

The activities of the Medical Research Council were much increased by the war. In its fifth report, for 1918–19, it is noted that "the stimulus and the special occasions of war have led to great progress in many parts of medical science. This has not only given direct aid in the practical conduct of war, but has led also to many permanent gains in scientific knowledge." In particular, much had been learned of wound "shock"; the replacing of lost blood; the respiratory system, through the treatment of patients suffering from gas poisoning; and of wound infection and gangrene. "If these advances made in wartime are to be continued and multiplied in peace, it may be well to note what the conditions have been that have allowed so many important contributions to medical science to be made during a time of such disaster and stress."

They were chiefly three: the availability of able men; immediacy of problems and the opportunity for investigation on

a large scale; and that "men fitted to the work have received —perhaps for the first time in the history of war, or indeed of peace—a large measure of public support."

The influence of national danger during war on the foundation of the scientific and industrial research councils of both Britain and the United States is notable. On these occasions, the fear of defeat was sufficient to make men and firms cooperate, and governments spend more money, in research. It is evident, too, that at these times the truth about motives and behaviour is often expressed in official publications with unusual candour.

The foundation of the British Medical Research Council arose, however, out of the legislation of the social reformers, who had passed the national laws of health insurance. But its development also owed much to the stimulus of the war of 1914–18. Medicine was advanced then as hospital services and surgery had been improved during the campaigns of the Roman legions. In England, as elsewhere, the poor physique of the recruits for the armies and the shortage of food stimulated much research on nutrition, and systematic attention to problems of industrial fatigue and psychology was encouraged, so that the output of munitions might be raised to a maximum. Lloyd George remarked in a foreward to a book on Welfare Work that "it is a strange irony, but no small compensation, that the making of weapons of destruction should afford the occasion to humanize industry."

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THE FINANCE OF RESEARCH

The most striking feature of this subject is the absence of exact information. No precise figures of the expenditure on scientific research in Britain are known, and efforts to collect them have only just begun.

The scale of the expenditure in the years immediately preceding the war of 1939 may be indicated by some rough estimates. The total income of the British universities was about £7,000,000 per annum. Only a part of this was devoted to teaching and research in science. Even if its size were exactly known, its analysis into expenditure respectively on teaching and on research would still be difficult. University science staffs and laboratories are usually engaged in both activities. But in place of a better estimate, it may be guessed that not more than ten per cent of the total income of the universities was spent on the salaries of scientists and the maintenance of their laboratories during that portion of their time spent on research. The total expenditure on scientific research in British universities was probably not more than £700,000 per annum.

The British Government's Department of Scientific and Industrial Research spent a gross sum of £872,127 in the year 1937–38. It maintained the National Physical Laboratory, with a staff of six hundred, the National Chemical Laboratory, the Geological Survey Museum, and research laboratories for the investigation of problems concerning fuel, food, building, roads, forest products and pollution; and it contributed £107,451 to research associations formed by firms in some twenty-two industries. It received £234,927 in fees for research,

advice and testing. For services rendered, £81,923 was paid by other government departments. Most of this, and in addition £69,822 in fees paid by private firms, was earned by the National Physical Laboratory. The gross cost of conducting the laboratory was £252,209, while its receipts were £141,302, so that the net cost was £110,907.

It will be seen, then, that the Department of Scientific and Industrial Research had a net expenditure of about £637,200. In the previous year the expenditure had been £583,230, so the increase for the year was about ten per cent.

The sum of £107,451 contributed to the activities of the research associations was supplemented by subscriptions of £232,468 from the associated firms. When the Department had been formed in 1915, it was granted one million pounds for establishing cooperative industrial research. It was believed that after this sum had been expended the various industries would have been convinced of the profitability of research, and would be prepared in the future to pay the whole cost of the work done for their benefit. The million pounds was exhausted in 1932–33, but cooperative industrial research was still not self-supporting. It was evident that if government support ceased, several research associations would be dissolved, their laboratories discontinued, and the work of the others ld be curtailed. Government support for the associations therefore renewed, and increased from £68,272 in 1932–33 to £107,451 in 1937–38.

The sums contributed were determined by a system of percentages of the sums subscribed by firms. It was evident that this system linked expenditure on research with prosperity in trade, for if the firms earned increasing profits, they would tend to spare more for research, while if their profits decreased, they would spare less, and accordingly the government contribution would decrease. Thus in times of depression both private and government expenditure would tend to decrease.

The Department also spent £26,391 on grants to stu-

dents to provide aid and apparatus for the prosecution of research.

The British Government's Agricultural Research Council provided for an expenditure of £111,922 in 1937–38. Of this, £38,640 was appropriated from the previous year. The total had risen to this figure from £15,525 in 1935–36. The Council also advised on the expenditure of the Departments of Agriculture on research and advice, so that, altogether, it influenced a total expenditure of £388,646 on research and advice in 1936–37.

The Medical Research Council received a grant of £195,000 for the encouragement of research in 1936–37. This was an increase of £30,000 over the previous year. It included £55,000 for grants to research workers.

The three research councils thus had a total budget of about one million pounds per annum. In addition to this, the British Government spent through its other departments, such as the Ministries of Health and Agriculture, an indefinite sum of about one million pounds on a variety of research and scientific advisory work. Further, in times of peace, the government spent probably about one million pounds per annum on scientific research concerned with military problems. Thus the total expenditure of the British Government in peacetime on activities that might be classified as scientific research was about three million pounds per annum.

The total expenditure of British firms on private research is quite unknown. Perhaps they spent as much as five million pounds per annum, but a large fraction of this would be devoted to the solution of routine problems arising in the manufacture and use of products. An estimate of two million pounds per annum would probably cover all activities which strictly involved some elements of research.

The total British expenditure by government, industry and universities on scientific research was probably not more than £5,700,000 per annum, at a generous estimate, and if the cost

of development work and routine research is included, not more than £8,700,000.

The First National Bank of Boston claimed that United States business alone was spending $200,000,000 per annum on various forms of research to develop new products and processes. This was equivalent to £40,000,000 per annum. The sum includes the cost of the adaptation of inventions for the market, and in many instances the expenditure on salesmen who reported on products in use in order to supply data for improvements. Other estimates give £47,000,000 as the total expenditure on scientific research in industrial, government and university institutions in the United States.

As the British national income was about five thousand million pounds per annum, the British people were spending only from one-tenth to two-tenths of one per cent of their income on research. The comparable figures for the American people are two-tenths to five-tenths of one per cent. Thus the rate of expenditure on research in the United States is about twice that in Britain, and the absolute expenditure is about five to ten times as great.

The figures are in fact much less favourable to Britain that they appear. Her chief laboratories are the central research institutions of the British Empire, for though there is a system of research organizations in the dominions and India, this is not yet very large. The most brilliant scientists born in other parts of the Empire tend to settle in Britain, as the career of Rutherford shows. He was born in New Zealand.

The expenditure of the British Empire on scientific research was certainly not double that of Britain alone, and yet it was to supply five hundred million people with the new knowledge which is the source of progress.

Expressed in another way, the British Empire spends perhaps ten million pounds per annum on research for the benefit of five hundred million people, while the Americans spend perhaps forty million pounds per annum on research for the

benefit of one hundred and fifty millions. According to this comparison, the Americans spend about twelve times as much for each person under their rule.

The situation in France was even worse than in Britain. No department of scientific research existed in France until 1933, and the expenditure of French firms on industrial research was very small. The output of research by the French universities was also small for the first decade after the war of 1914–18. This situation was due to various factors. A very large number of young Frenchmen were killed. Of the students at the Ecole Normale at the outbreak of the war, eighty per cent were killed and of those at the Ecole Polytechnique, ninety per cent. These were the flower of French youth. When the war was over, there were few young scientists to succeed the older professors. The scientific interests of these older men had been fixed before the development of the quantum theory of relativity, so they were exclusively interested in classical physics. There were few men of the middle generation to preserve continuity between the old and the young men, and the situation became worse than disconnected. Many of the old professors definitely attacked the new science, and discouraged its development. Another unsatisfactory feature in France was the concentration of ability in the capital. Scientists regarded provincial universities as mere stepping-stones to Paris.

The effects of these developments were ignored for the first decade after 1918. The French nation was politically and financially powerful, and could obtain what it wanted without intense efforts in science. Its business men were not interested in research, because they were prosperous and had no difficulty in buying the rights in any valuable inventions made abroad.

But perspicacious Frenchmen presently became disturbed. They noticed the tremendous development of science in the German Republic, accompanied by the production of new processes and the rationalization of industry. Accordingly, in

1933, the Minister of Education founded a Council of Scientific Research, because "disinterested researches in pure science are the source of all progress in human powers," and "apart from motives of idealism and prestige it is of practical importance to discover those capable of scientific research." A national fund for scientific research was formed in 1935. When the government of the Popular Front was elected, the framework of a state organization of science was already formed. It was immediately strengthened by the appointment of Mme. Irène Curie-Joliot as Under-Secretary of State for Scientific Research. This was the first occasion on which a scientist, as such, was "taken into the counsels of the French nation." She was succeeded by J. Perrin, the eminent physicist.

The conditions and atmosphere of scientific research were quickly changed. Perrin, Langevin, and the new school of younger scientists believed that the cultivation of pure research is necessary to the dignity of the human spirit, and that science provides the only means for the liberation of humanity from the restrictive conditions of nature. They gave aggressive expression to the French tradition of intellectual freedom and culture. This spirit was exemplified in the differences between the French Department of Scientific Research, and the British. The French insisted that the secretaries of their Department should not resign from research. They were appointed for periods of five years only, and were then to return to the laboratory. Perrin retained his academic professorship while he was Minister. Precedence was given to cultural over governmental values.

In Britain, governmental prestige is valued more highly, and the majority of British scientists would probably be glad to resign from research permanently, in exchange for high administrative position.

The expenditure on the new department in 1935–36 was £160,000, compared with £572,000 for the British Department of Scientific and Industrial Research. It rose to £240,-

000 in 1938. The French have no National Physical Laboratory, and would be glad to have one.*

Their system of grants to aid research workers has had a very important part in reviving science in France. They gave £100 per annum for trial scholarships in research. If the candidate was successful, he became a recognized research worker, with a salary of £200. After the publication of approved research, he was raised to the status of master, with status equivalent to that of an assistant professor. If very successful, he became a director of research, with the status of a full professor. The highest salary paid to a professor in Paris, in virtue of one appointment, was about £600 per annum. The cost of living in France was lower than in England, so this figure is not directly comparable with the corresponding figure in England.

In 1936 about 350 research workers in France were assisted in this scheme. Joliot benefited from it during the period when he was making his researches that led to the discovery of artificial radioactivity.

The Department of Scientific Research has since provided large sums for his new laboratory for nuclear chemistry in the Collège de France. It contains eight floors, and a thirty-two-inch cyclotron, and magnificent equipment and workshops. The special Wilson chambers used by Joliot in his researches on the disintegration of the nuclei of uranium atoms were elegant pieces of workmanship.

The department also built for Joliot a high-tension laboratory at Ivry, near Paris, at a cost of £40,000, to be equipped with a three-million-volt impulse generator, and a five-million-volt Van de Graaff apparatus. He was also to have had a fourth type of high-tension apparatus, a 200-kilowatt million-volt transformer. He aimed at the simultaneous exploration of all methods, and he considered that the development of research should start with the discovery and the encouragement of men rather than the building of institutions.

* This paragraph was written in 1939.

The system of bursaries was of great assistance to Joliot's school. He had twenty research colleagues at the Collège de France and ten at Ivry, and many of these would not have been able to work with him without the bursaries. He was glad to count Italians, Russians, Poles, Austrians, Palestinians, as well as Frenchmen among his colleagues. Joliot was deeply interested in the internationalizing influence of science. He had noticed that men of all nationalities, when they have worked together in the laboratory, tend to preserve contact when they return to their own countries, whereas the study of literature seemed to encourage nationalism.

The brilliant work of the younger French scientists raised much hope, but the support for scientific research was quite inadequate. The French expenditure on research was probably less than half the small sum spent by the British.

The financing of scientific research in Britain, and in France and America, is chaotic. No one knows how much is actually spent on research, and those who seek support must collect it in driblets from many places. When a young British scientist does good work and is appointed to a chair at an early age, he finds that his opportunities have not always increased. He may succeed an elderly man whose laboratory was out-of-date and not equipped for modern research. He then has to find the money for improving his laboratory. At the best, this is done by preserving good social relations with monied sources; at the worst, it degenerates into fantastic cadging. Sometimes he becomes the victim of the new habits, and changes from an investigator into a politician of science.

He may have to collect grants from several different sources for the support of his research assistants, £200 from one firm, £100 from a second, and £50 from a third, and so on. This involves attendance at series of committee meetings.

If his department is large, he may not be able to work at his laboratory bench for periods of years. Most of his time will be devoted to attending university senate meetings, writ-

ing testimonials, etc., and he will not be able to do more than supervise a team of research assistants.

Much of the energy of the best scientists in Britain is wasted on collecting money for research and in departmental administration. In America, the lawyers of sick millionaires are sedulously courted by the directors of some scientific institutions, with the hope of receiving new endowments for research. This could be prevented by a better method of financing research. The sources of funds should be pooled, so that the professor would not have to apply to one or two places for grants.

The explanation of the situation is clear. Scientific research arose as a response of individuals to their environment. They did not see any reasons for stating their expenses and, as private persons, they could not be called upon to publish them.

The same tradition continued when research was pursued by private firms. As research was not originally brought into existence by a conscious system, it did not proceed according to a plan. It shared the general characteristics of the society of private enterprise in which it developed.

In countries such as Britain and the United States, the moulding influences of government on industry followed the private development of industry, and the same history is being repeated with the organization of science. The financing of research in Britain is now too large a matter to be left to the enterprise of individual adjustment. When science was inexpensive, organization did not matter, but the sums needed for modern research are too large for casual handling.

There is a necessary evolution towards the planning of the finance of research. Perhaps British research could be helped best by the creation of a national research fund. The Association of Scientific Workers has estimated that a fund of thirty to forty million pounds is desirable. It might be raised from customs duties that have been designed to assist British industry in the home market. The total is about equal to the subsidies

that have been paid by the government to the sugar-beet industry.*

Such a fund would relieve men who can do creative work from wasting their time on soliciting and administration, for which they are often unfitted. It would provide adequate laboratories and equipment and satisfactory salaries and permanency of appointment to men of proved ability.

Something of the sort has actually happened, in a partial and haphazard way. The establishment of the duties on imported motorcars provided the situation in which certain British manufacturers of motorcars made very large fortunes. Parts of these fortunes have since been devoted to the endowment of medical and scientific research.

The British Department of Scientific and Industrial Research has published striking estimates of the economic value of scientific research. They have shown that expenditures by them on research in the blast furnace, electrical, food, and cotton industries, which *totalled* £440,000, led to *annual* savings in those industries of £3,250,000. One wonders why business men and statesmen do not jump at once into lavish expenditure on research. The reason is that the savings which accumulate into these large figures do not benefit any small group of persons, but are spread in small amounts to the members of the whole of the community. Nevertheless, the saving exists, so the government would be justified in putting comparable sums on one side for the endowment of further research.

The government grants to students are on the most meagre scale. In 1936–37, the Department of Scientific and Industrial Research awarded eighty-one maintenance grants to research students.

The Royal Society, the Royal Commission for the Exhibition of 1851, the Department of Scientific and Industrial Research, the Medical Research Council, the Leverhulme Fund,

* This paragraph was written in 1939.

and some other bodies award altogether about one hundred senior research fellowships every year. The total of these annual expenditures is of the order of £100,000. It is small compared with the munificence of the Rockefeller Foundation, which spends about £2,000,000 yearly on the support of research in general and social science, nearly half of this sum being spent on workers outside the United States.

Grants to students by the Department of Scientific and Industrial Research are governed by a peculiar circumstance. If the student works at Oxford or Cambridge, he may receive aid up to £250 per annum, but if he works in a provincial university, it will be limited to £120. This hinders the professors and departments in the provincial universities from getting the best research students, for these naturally go to Oxford and Cambridge, under the attraction of the higher grant.

Generous provision for research is essential for national security, besides the advancement of civilization. A nation of forty-five million persons in a small island will have increasing difficulty in competing with nations of one hundred millions settled in compact Continental blocks. Superior technique is essential for survival in such a situation, and the largest expenditure and most thorough organization are justified to secure it.

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PLANNED RESEARCH

The only country in which scientific research has been consciously planned on a national scale is Soviet Russia, where society has been reorganized according to the principles of Marxist philosophy. Marx had acquired an evolutionary conception of history from Hegel, who conceived history as evolving according to what he named the dialectical process. In this, the development started with the growth of an idea, which simultaneously brought into existence its opposite. The conflict was resolved by progression to a new idea, which in turn brought into existence its opposite, and so on. The Hegelian dialectic had been derived from Greek dialectic, or argument, which aimed at the discovery of truth by propounding ideas, and proceeding to truer ideas through contradiction and discussion. Hegel had attempted to raise the ordinary method of progression towards truth by argument to a philosophical principle, and he conceived history as the result of the Absolute Idea progressing towards truth by eternal argument with itself.

Hegel named the growing idea the thesis. Its opposite was the antithesis, and the conflict between them was resolved in the new synthesis. Marx found this terminology useful in describing the movement of history, which he regarded as the development of a series of class conflicts. He identified one class with the thesis, the conflicting class with the antithesis, and the resolution of their conflict the synthesis. Thus the evolution of history in the modern period was governed by the capitalist class as thesis, the working class as antithesis, and socialism as the synthesis in which their conflicts would be

resolved. But the content of Marx's philosophy was entirely different from Hegel's. "My dialectic method is not only different from the Hegelian, but is its direct opposite. To Hegel, the life-process of the human brain, i.e., the process of thinking, which, under the name of 'the Idea,' he even transferred into an independent subject, is the demiurgos of the real world, and the real world is only the external, phenomenal form of 'the Idea.' With me, on the contrary, the ideal is nothing else than the material world reflected by the human mind, and translated into forms of thought."

Marx based his philosophy on the properties of the real world, and therefore on natural history. Science was a fundamental part of its structure, and he viewed the evolution of society "as a process of natural history." He regarded Darwin's work as doubly important, because it dealt with some of the data of natural history, and also because the meaning of these data was analyzed with the assistance of the concept of evolution, and he had already adopted both data and concept as basic to his philosophy before Darwin's work was published. These were not the only features of Marx's philosophy which have proved convenient for handling scientific ideas. The principle of contradiction, or unity of opposites, is fitted to describe such notions as the modern wave-and-particle conception of the constitution of matter.

Further, in the development of his social theory, he attributed a fundamental rôle to science and technology. In his view, socialism would have been a utopian dream if production, through the agency of science, had not been multiplied to such a degree that equal means, which are the basis of social equality, could be supplied to all.

When the government of Russia was undertaken by men with Marxian views, the development of science and technology became a necessary part of the society's life. This was a new feature in government, for in other countries science was not held, in theory, to be necessary in social organizations.

For instance, science had little part in the education given at Oxford to future administrators. The majority of these studied ancient and modern literature. This taught them the methods used by politicians in the past. They learned how to find a place among groups of persons who held power and the arts by which they might be influenced. They mastered the verbal dialectics which give power in committees and Cabinet meetings and the technique of public speaking. They regarded science as a useful but inessential appendage of the state, and would not have been embarrassed by its disappearance. This view is illustrated by the composition of the six hundred members of the House of Commons. In spite of the importance of science in modern life, not one of them is a working scientist.

Lenin was aware on philosophical grounds that science should be an integral and not an accessory part of the social system, and he said in 1920 that "not until the country is electrified, and our industry, agriculture and transport are built upon the foundations of up-to-date large-scale production, shall we be finally victorious."

Plans were accordingly prepared for the construction of a social system in which science and technology had an essential rôle. The starting point of the planning was an estimate of the requirements for creating a satisfactory standard of life for everyone. It was relatively easy to calculate how much food, clothing, housing, medical service, etc., would be needed to provide comfort and health. From these figures, estimates for the size of the industries for supplying them could be calculated. An output of so much agricultural goods, so much coal, oil, iron, ores, etc., was necessary. The required quantities were far larger than those hitherto produced. The planners therefore considered, for instance, how the output of agriculture might be increased. A system of research institutes was created to assist in the discovery and introduction of better methods.

Very large surveys of the natural resources of the country

were made, to find the necessary supplies of minerals, and these yielded much new geological knowledge.

The requisite metallurgical industries called for institutes where the problems of metallurgy, refractories, and operation could be solved.

A very large electrical industry was planned, to supply power for the manufacturing industries and light to the population.

The number of scientific problems whose solution was made urgent inspired the revival of the Academy of Sciences. This had been founded by Peter the Great, after the model of the French Academy. It had been founded as an emblem of power, an ostentatious demonstration of the wealth which gave clever men the leisure to perform impressive feats of intellectual skill, rather than as an organic part of the state. The scientific demands created by the new planning led to a fundamental reorganization. Its first duty under its new statutes was to direct the study and application of science towards the fulfilment of socialist construction and the growth of socialist culture. The Academy, which formerly had been restricted to pure scientists, was opened to technicians and social scientists, and its numbers increased to about a hundred.

The plan of work for 1932–37 was based on seven general subjects, which were:

1. The structure of matter, and its bearing on astronomy, physics, chemical physics and chemistry.
2. The survey and utilization of the natural resources of the U.S.S.R.
3. The survey and planning of the power resources of the U.S.S.R.
4. Problems of distribution, building materials, hygiene, etc., arising out of construction.
5. The general introduction of chemistry in industry and agriculture.
6. The study of biological evolution, and the bearing of its results on agriculture and materials for light industry.

7. The provision of the historical and social theory for combating the ideas of capitalism and dissolving the prejudices which survive in the minds of the people and have been transmitted from earlier forms of society.

This reorganization gave the Academy a working rôle in the state, and transformed it into a purposeful institution, directing numerous institutes and expeditions and several thousand research workers of various qualifications.

The development recalls George Ellery Hale's reflections, in his introductory paper on the founding of the National Research Council in the United States, on the effect of the French Revolution on the French Academy. He said: "In spite of the devastation of the Terror, which included Lavoisier among the victims of the guillotine, science attained a prestige far higher than it had ever known during the tranquil days of the old régime. The nation instinctively turned to the Academy for advice and assistance in the initiation of many new enterprises, and ministers, parliaments, administrators and state assemblies often sought its aid and accepted its decisions. The leaders of the Revolution, and subsequently Napoleon himself, re-established the old Academy on firmer foundations and accorded it privileges never experienced under the monarchy."

The Soviet organizers regard the human ability in their country as one of their chief natural resources. Special institutes are built for men of notable genius. The application of ability to unsuitable tasks is bad planning because it is an abuse of part of the society's most precious resources. Planning is regarded as the aid which will provide able men with better opportunities, and the belief that it is intrinsically inimical to creative work is considered mistaken. This is the explanation of the apparent paradox that while the Soviet has planned research, it has given quite exceptional facilities to outstanding individuals.

The planning of research associated with the electrical in-

dustry may be taken as a general example. The required output of electrical units was estimated, and plans were made for the requisite number of electric power stations to supply them. The stations, and the transmission system that they supplied, had to be designed, built, and operated. This presented all the usual problems of electrical engineering, and new ones arising out of special conditions or previously not occurring in practice.

Much can be done in building such a system by buying foreign machinery and engaging foreign experts to operate it, but this does not provide a permanent solution. Even for efficient operation alone, men with the training and ability to solve new problems are necessary, and cannot be continually sent for from distant countries.

A big electrical industry accompanied by a system of research institutes where its problems might be solved, and the most skilled of its technical staff trained, had to be set up.

The research institutes whose work was associated with the electrical industry were organized under a scientific office of the department of state directing the heavy industries.

Their programmes of research were coordinated through a series of about a dozen committees, each containing ten to fifteen members. They held two or more meetings in the year. Each committee prepared a plan for research in its subject for one year, and laid down the general line of the work for each related laboratory. They apportioned researches among the various institutes, so that overlapping was avoided and particular problems were studied in the places most suitably staffed and equipped. The work done in the year was reviewed and assessed at the second yearly meeting.

The work of these committees was done mainly by correspondence. The majority of their members were directors of institutes, and this committee work occupied perhaps two full weeks' work spread through the year. These committees also

decided the size of the allowances for books and periodicals, and arranged conferences on research and organization.

The methods of planning have been changed rapidly, but some details of the system used in the Physico-Technical Institute at Kharkov in 1935 will illustrate the mode of approach.

The laboratory staff made a plan for the year and four quarterly plans. They were used as guides and the adherence to them was not mechanical. A research worker could not change his subject without wide discussions with the rest of the staff.

Workers engaged on the same group of problems were organized in brigades, which held their own meetings, to discuss the best way of accomplishing their programmes, and worked with collective enthusiasm. An individual's personal desires received little consideration, but if he could persuade his brigade to adopt his proposals, they were put through with more force than he could have exerted by himself. In practice, a competent person could usually obtain the backing of the institute for good suggestions for research. If a brigade accomplished a good piece of work, some of its members may have received publicity and honours. These were given to the recipients as representatives of their brigade, though they might in fact have been received by the men who originally made the proposals. In this way, the growth of fame was combined with Communist principles.

The organization of workshops was particularly thorough. A cheque book was attached to each research problem. The cost of the apparatus made for it in the workshop was recorded, so that the cost of each research was known and also the comparative speed of the various mechanics at their work.

The staff of the institute included 230 persons, of whom thirty-four were members of the Communist Party or candidates for membership. These formed a Party cell, which provided the main inspiration of the institute's activity. They held private and public meetings among the staff, to discuss

difficulties and see how they might be solved and how the institute could do its share in assisting the general aims of the Executive Committee of the Party.

Discussions of all the scientific interests of the institute and the main political questions of the day made the life of the staff lively and enthusiastic. The trained research staff contained about fifty scientists, nearly all less than forty years of age. Their work was concerned chiefly with high-tension physics, spectroscopy, low-temperature physics, X-ray analysis, fluorescence, photoelectricity, cosmic rays, and crystal structure.

The annual budget for running the institute was 1,500,000 roubles in 1934, and thirty-five per cent was spent on light, heating, etc., and purchasing and making equipment. There were seventy-eight assistants, seventy mechanics and workshop staff, and thirty-five janitors, handymen, etc.

It is difficult to estimate the value of the rouble, but it was probably about twenty to forty to the pound in this expenditure, so the running cost was from £37,500 to £75,000 per annum. The building was of a type that would cost perhaps £200,000 in England.

Whatever may be thought about particular events in connection with the Soviet Union, it is certain that its scientists have accumulated unique experience in making the first planned system of scientific research. They were the first to give conscious expression to the unconscious tendency to organize research which is seen in all countries.

Their pioneer effort did not make rapid progress until about 1924, when the country was beginning to recover from the effects of the war, so their system is not effectively more than fifteen years old. The numbers of new young scientists are still raw, and many troubles have arisen through immature or insufficiently trained men trying to accomplish too difficult tasks. The violent contests over political policy have been reflected in the life of the institutes and, as in other departments of the

state, many scientists have been imprisoned, and some have been shot. Insufficiently educated enthusiasts sometimes denounced scientific theories because they were advocated by persons whose political views were regarded as inimical to the state. The scientific researches of persons disapproved by the political authorities have sometimes been omitted in lists of references, and scientists have sometimes been seen apologizing to the political authorities for having held opinions which appear to the majority of the scientists in the world to be correct.

These imperfections are due to the limitations of mankind. The Russian Marxists have accomplished a prodigious social revolution, and its full effects, like those of the French Revolution, may not be clear for another century. In spite of the crudity, violence, and less noble manifestations, much of which may be attributed to short-sighted opposition, they made the first model of a system of research some of whose features will inevitably be adopted elsewhere. If they introduce a social policy incompatible with the development of science, their system must decay, as science and technology are an essential part of its foundations.

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78

AMERICAN FORESIGHT

The development of the United States was conducted under the initiative of private enterprise. During the latter half of the nineteenth century its governments were, on the whole, satisfied with the developments when the leaders of private enterprise were satisfied with them. They did not feel called on to question some of the peculiar phenomena that accompanied this development. It was assumed that if individuals or classes of persons suffered from its effects, this was their own fault. The governments believed that private individuals and corporations should not be prevented from doing what they liked with their own, even if the community suffered from some of their actions. They felt that on the balance, private enterprise did more good than harm, and that if the harm were stopped, the greater good would stop also. The harm was the inevitable accompaniment of progress, and could not be mitigated. It was not the business of the governments, and was therefore not investigated by them.

This general view had always been contested by a minority, but without much effect until after the end of the war in 1918. Catastrophe had heightened many of the anomalies, and at the same time victory had provided the optimism that inspired hopes of better social construction.

The eminent mining engineer H. C. Hoover, whose edition of Agricola was of such help for Section 52 of this book, had become famous as a world organizer of relief during the war. He was drawn into politics through his administrative abilities, and in 1921, as a statesman, he began to sponsor enquiries

into American society, to discover whether it could be improved by action based on accurate knowledge of some of its features. Under his chairmanship, a notable report on *Waste in Industry* was prepared in 1921. After he had been elected President of the United States, he appointed in 1929 a group of scientists to make a survey of American society, to obtain accurate knowledge of its stresses as data for the preparation of policies to deal with them constructively. This committee published its findings under the title of *Recent Social Trends* in 1932. It had noted a bewildering confusion of problems, ranging from foreign policy, governmental regulation of industry, urbanization, shifting moral standards, etc., to the future of democracy and capitalism. The combination of immigration from many lands and swift development of natural resources had hurried the nation at a dizzy pace from the frontier life into a whirl of modernism.

A marked indifference to the interrelation among the parts of the huge social system accompanied this amazing mobility and complexity. "Powerful individuals and groups have gone their own way without realizing the meaning of the old phrase, 'No man liveth unto himself.' "

Splendid technical proficiency was exhibited in some incredible skyscraper, while monstrous backwardness was to be found in a neighbouring, equally incredible slum.

America's outstanding problem was to realize the interdependence of the factors in its complicated social structure, so that the advancing sections of its forward movement "in agriculture, labour, industry, government, education, religion and science may develop a higher degree of coordination in the next phase of national growth." Its investigations showed that American life was strained by unequal rates of change in its parts, as if "the parts of an automobile were operating at unsynchronized speeds." It noted that "scientific discoveries and inventions instigate changes first in the economic organization," and the social habits most closely connected with

it, such as urbanization, and labour organization. These in turn influenced the institutions of the family, government, schools and churches. Industry and government were gaining regulatory influence over the population at the expense of the church and family. Technology and organization had affected spiritual values. This made moral guidance in the present peculiarly difficult, because moral values had been evolved through long periods when social conditions were very different. The committee did not believe that the enhanced difficulties of modern times could be solved by a moratorium on research in physical science and invention. It held, on the contrary, that social invention should be stimulated to keep pace with mechanical invention.

It had found that there was much poverty in both rural areas and cities, even during the prosperous years from 1925 to 1929. The American people devoted far more attention to making money than to spending it, and there was need for the promotion of special organizations to advance the interest of consumers.

The family had been the chief unit of economic production in former civilizations. The growth of the factory system had destroyed this part of its functions, and had loosened its unity. Few families in any cultures have had as little economic function as those that live in American city apartments. Figures showed the probability that one out of every six couples married in 1932 would ultimately be divorced. This might be reduced by founding institutes for the study of happiness. It has as yet received little scientific study, though it is one of the most cherished ideals.

The Church's influence over behaviour had declined, and yet "from 1906 to 1926 the wealth of churches increased more rapidly than did the national income." Nevertheless, there were forty-four million church members, whose youth organizations included six million; and the property of the churches was valued at seven thousand million dollars.

The American people spent about twelve thousand million dollars annually on entertainments, ranging from sport and the cinema to motor touring and radio. The number of journalists providing reading matter had increased by ten times between 1870 and 1930. "Americans have but scanty traditional equipment for amusing themselves gracefully and wholesomely," and they should give more earnest attention to this problem.

After its wide survey, the Committee concluded that the people of the United States must make important reorganizations in its social life, especially in the economic and political aspects, and stop drifting. They must recognize the rôle that science and technology would play in such reorganizations. Some recognition of the need for finding the exact facts of American life had been obtained, and the next step would consist in devising a policy based on these facts. It noted that the federal government and cities had already done much social planning, and it anticipated that far more would be done by them. A National Advisory Council might be formed, which would include scientists, educationists, statesmen, economists and others, who would consider the basic social problems of the nation, "always in their interrelation, and in the light of the trends and possibilities of modern science."

It did not wish "to exaggerate the rôle of intelligence in social direction." It admitted the importance of tradition, stupidity, the raw will to power, and other factors, but too much preoccupation with them led to "hopeless resignation."

The alternative to constructive social initiative might be drift, punctuated by make-shift readjustments.

But there were more definite alternatives in dictatorship, in which violence may supplant technical intelligence in the direction of social change. Unless there was a more impressive integration of social skills and purposes than was revealed by recent trends, there could be "no assurance that these alterna-

tives, with their accompaniments of violent revolution, dark periods of serious repression of libertarian and democratic forms, the proscription and loss of many useful elements in the present productive system, can be averted."

The social maladjustments described in this report were greatly exacerbated by the depression of 1929, and their reverberations led to the defeat of Mr. Hoover himself in the Presidential election of 1932. But the administration of his successor, Mr. Roosevelt, continued and extended his line of investigation. The administration's National Resources Committee organized a study of technological trends, including the social implications of new inventions, through its science sub-committee, and published a report on Technological Trends and National Policy in 1937. This was transmitted to Mr. Roosevelt as "the first major attempt to show the kinds of new inventions which may affect living and working conditions in America in the next ten to twenty-five years. It indicates some of the problems which the adoption and use of these inventions will inevitably bring in their train. It emphasizes the importance of national efforts to bring about prompt adjustment to these changing situations, with the least possible social suffering and loss, and sketches some of the lines of national policy directed to this end."

The report contained a large collection of facts about contemporary American agriculture, transportation, communication, power; mineral, metal, chemical and electrical industries; and constructional engineering. A glance at these reveals some of the chief directions of change in American life.

In 1787, the surplus produced by nineteen farmers was required to support one city dweller. At present, nineteen farmers produce on the average sufficient to support fifty-six city dwellers and ten foreigners. Crop production increased by 27 per cent in the interval 1922–26, while the crop acreage remained almost constant and the number of agricultural workers decreased. Between 1918 and 1932, ten million horses and

mules were displaced by automobiles. This released thirty million acres of grazing land for the production of salable commodities.

The domestic consumption of farm products remained relatively stable during the years 1930 to 1933, in spite of very low prices. It was concluded that it is doubtful if any but the very poor would consume much more as the result of a substantial increase in income.

American farmhouses were still very backward. Only about 15 per cent had electricity, 27 per cent kitchen sinks and drains, 17 per cent cold water laid on to the house, 8 per cent a constant hot-water supply, 9 per cent flush toilets, 8 per cent furnace heat, and 4 per cent gas or electricity for cooking. In Holland, 100 per cent of farms have electricity, and in Germany, 90 per cent. Snow surveys were being made to improve the forecasting of the supplies of irrigation water. Improvement in the breeds of maize plants had produced an increase of 15 per cent in yield, so that an equal quantity could be obtained from a smaller acreage. This required less labour and tended to create unemployment.

Careless methods of farming sometimes give better results than apparently more scientific farming. This has happened in tobacco-growing. If the ground is allowed to run to weed, it subsequently produces a better crop than by any known system of cultivation. The tobacco has a superior quality, and the increase in the value of the crop is about two hundred dollars an acre.

The concentration of cattle-rearing in ranches is due to the necessity of keeping a large number of cows within reach of one bull. The development of an artificial insemination service, by which superior germ plasm may be distributed in capsules through the post, may enable the small farmer-breeder to compete with the rancher.

Enormous economies may be made by successful suppression of insect pests. The boll weevil destroys about 2,000,000 bales

of cotton annually, and the Hessian fly 48,000,000 bushels of wheat.

A great deal remains to be learned of the science underlying such possibilities. It is estimated that there are about 4,500,000 species of insects, but only 750,000 have as yet been described. Seven thousand species are known to cause economic damage in the United States. Many American farmers demanded low-grade fertilizers. These are made by diluting high-grade fertilizers with fillers. The farmers of the Southern states pay about five million dollars a year for fillers that have no agricultural value. The diluted fertilizer is somewhat easier to apply.

The estimating of cotton crops has been improved by a cropmeter device that may be attached to a motorcar driven along the fields. A new market for cotton may be found in the reinforcing of asphalted roads.

The elimination of forests has removed the natural sponges for moisture, and has increased desiccation and dust storms. The dust storm of May, 1934, shifted three hundred million tons of fertile top soil. The wind erosion increases the destructiveness of water erosion. Four hundred million tons of material are carried into the Gulf of Mexico every year by the Mississippi. Deforestation, which has such a serious influence on erosion, is a result of exploitation. About 98 per cent of the forest products of America are provided from private forests.

The restoration of an equilibrium in land life is essential to the security and permanence of America. The scientist and technician must find ways whereby restored forests may perpetually supply the products at present obtained from resources that cannot be renewed.

The increase of tenancy among farmers in Texas has grown from 38 per cent in 1880 to 57 per cent in 1935. The corresponding figures for the Mississippi are 44 per cent and 70 per cent, and in Alabama 47 per cent to 64 per cent. The gross farm income in ten cotton states was $1,571 in 1929, and $669

in 1934. In the remainder of the United States, the average was $2,414 and $1,353 respectively.

Tremendous effects are to be expected from the successful introduction of the machine for picking cotton. It would cut down sharply the greatest single source of employment of woman and child labour in America. It might free labour for imported industries from the Northern states, and it might raise the wages of the head of the family and leave more means for education.

As for the mineral industries, 90 per cent of power is still drawn from minerals, and only 10 per cent from water. But mineral technology works with an increasing handicap as mines become poorer and deeper. No new fields of mineral deposits have been found in the United States since 1910. The known deposits of coal would supply the present rate of consumption for two thousand years.

The deposits of oil known until recently were sufficient only for some ten years. But fifty new oil and gas pools were discovered in Texas alone in 1935. This was largely due to geophysical methods of prospecting. These found much oil and underground water, but few new metal deposits.

Until recently, American coal mines shovelled each year a quantity of coal equal to the total weight moved in the excavation of the Panama Canal. In 1923, this was virtually all done by human muscle alone. Since 13.6 per cent of all bituminous coal is now loaded by machinery. The substitution of machines for human muscle is at the maximum in open-cut mining, where the mineral is lifted by mechanical shovels that raise thirty-two cubic yards at each bite. These machines will sometimes shift beds of limestone, and permit the economic removal of fifty feet of strata to reach a five-foot seam of coal. It is expected that open-cut mining will increase. It needs only a half or one-third as much labour as underground mining.

The number of bituminous coal miners declined by 247,000

between 1923 and 1935. Nevertheless, the long-run effects of mechanization are beneficial to the miner, and in any case technological progress is essential to meet the growing competition from petroleum and natural gas.

The depth of mines will be increased by refrigeration. The Robinson Deep gold mine in South Africa sinks 8,500 feet, and has the largest air-conditioning plant in the world. Some believe that the output of gold from the world's mines may increase greatly through this innovation, and will allow all countries to return to the gold standard.

Wastage in contemporary mining is great. This is offensive to the merest common sense, but as it is a wastage of non-renewable material, it is also a major social problem. The elimination of waste is one of the factors which is reducing the amount of transport in manufacturing processes. The transport and re-melting of pig iron in the manufacture of steel has recently been eliminated by using hot molten iron direct from the blast furnace for steel-making. The more efficient use of coal in domestic heaters and general economy of fuel will tend to reduce freight transport. The increasing durability of metal products and alloys will reduce renewals, and hence future production and freight. It is estimated that the steel produced in 1935 will last on an average thirty-two years, and twice as long as the steel of 1885. The pipe lines delivering natural gas from wells provide a substitute for 40,000,000 tons of coal a year. It is not impossible that in the future all coal will be turned into gas or oil, and delivered through pipes, eliminating rail and ship transport of coal.

Some reduction may come through legislation against smoke. This leads to economy in fuel. The electrification of city railways has not been due, so far, to this motive, but to the superior capacity of electrified systems for handling heavy traffic. Diesel locomotives have many advantages. They are lighter, and make no smoke. Moreover, they are not affected by cold

weather, which reduces the power of a steam locomotive by one-third.

The average American travelled 2,000 miles in 1929 compared with 500 in 1920. This increase was chiefly due to the motorcar. The berths in trains had not been substantially changed for half a century, but the competition of other modes of travel has already brought about a change. Berths in transcontinental planes are both longer and wider.

The growth of aviation should benefit employment, as it requires an exceptionally large ground staff. Motor lorries also need much accessory labour; about twenty to thirty times as much as the railways per ton mile. "Shorter hours, higher wages, greater old-age security and better education will favour increased passenger travel, just as the long hours and poverty attendant upon farming submarginal land virtually root people to the soil."

Improved electrical communications should provide the possibility of having one's newspaper printed in the home from a central office. News should be seen and heard in the making. The contents of documents should be swiftly transmissible. The ability to see and hear persons at a distance, whether in the airplane, motorcar or steamship, will produce an outlook quite different from that limited by vision, horizon and social contact.

The education of the child and the public should be revolutionized, and the future man may be far better trained for thinking than the present man. The speed at which some of these developments are occurring is illustrated by the sale of radio receivers for automobiles. This reached one million in the United States in 1935, and formed 18 per cent of the trade in receivers.

The rapid introduction of the dial system in telephony was due in part to its special advantages in serving a cosmopolitan population.

The improvement in the steam industry, which is the oldest of the modern forms of power, are among the most striking in recent decades. Steam is still very definitely holding its own. The cost of steam power plants for producing electricity is about \$75 to \$125 per kilowatt. In 1880 the consumption of coal needed to produce one kilowatt for one hour was 10 lb. In 1900 the figure had been reduced to 5 lb.; in 1918 to 3⅓ lb., and in 1935 to less than 1 lb. The cost of transporting coal 900 miles is no greater than conducting electricity 200 miles.

There is still room for an enormous increase of the grid system. Less than two-thirds of the urban population have houses wired with electricity. It is expected that overhead wires will be replaced by cables. Meters will express the consumers' bills in an easily readable form. The cost of repairs will be reduced by rationalizing distribution in cities through the construction of special tunnels for water, gas, sewers and communication. These will remove the need to dig up the streets.

There will be a steady increase of automatic working in chemical plants. Its aim is not the reduction of labour costs by eliminating hands, but accuracy in operation, improved uniformity in the product, and hence lower over-all costs. Automatic and remote control is simplifying architecture. In one plant \$500,000 worth of instruments are already used for automatic control. A fair-sized alcohol-distillation plant operates with one man per shift.

The introduction of lead tetraethyl for removing knock in motor engines created a demand for bromine. A great plant for extracting bromine from the sea was built to meet it. In 1935 it recovered bromine from the sea at the rate of 600,000 lb. per month. Gold exists in the sea, in about four parts to the thousand million, and may be extracted from it in the future. Other products that could have been recovered were salt, magnesium sulphate, calcium chloride, potassium chloride, magnesium, aluminium, strontium carbonate, iron, copper, iodine and silver.

Progress has already been made towards the replacement of natural by synthetic rubber. A factory covering an acre will produce 200 tons of synthetic rubber in two hours, while five years are needed to produce 500 lb. of rubber from an acre of rubber trees.

There will be an increasing use of chemicals for treating insects and plant diseases. These cause an annual loss to the United States of $3,500,000,000.

The kingdom of chemical synthesis has been created in addition to the animal, vegetable and mineral kingdoms. It will not be possible to govern this new kingdom without adding a fifth estate of scientists to the estates of the lords of the spirit and the earth, the commons, and the press.

Great developments are anticipated in lighting. Tungsten wire lamps give 2.2 per cent of the energy derived from coal as light. The fire-fly gives 96.5 per cent light for its consumption of energy. This is produced by the oxidation of a substance named luciferin. If this could be synthesized cheaply, it would provide a nearly 100 per cent efficient light, diffused, without glare, and involving no fire risk, because it would produce virtually no heat. More may be expected from luminescent paints, which will store up sunlight during the day and glow in colours at night.

Air-conditioning plants will become universal. Patents for them have been registered in the United States at the rate of 300 a day. Streets will be better illuminated. Accidents are 58 per cent higher between 5 and 8 P.M. in winter than in summer. The return on the investment in roads is lower than it might be, because 80 per cent of the traffic travels by day. The ratio of accidents between night and day is 8 to 1 for well-illuminated streets, and 47 to 1 for badly-illuminated streets.

Photoelectric cells are already used for hundreds of automatic operations in the metallurgical and chemical industries, counting, sorting, opening doors, etc. At least one million workers could be replaced by them now. Electric timing may

be used for roasting beef, turning on lights and heating, etc., when the occupant is away or sleeps.

The increase in the variety of metals is enormous. Already five thousand alloys are in use, and the value of non-ferrous metals produced already exceeds that of the world production of iron. The efficiency of production is rapidly increasing, and there is little doubt that it will produce unemployment among metal workers.

"Technical men are repeatedly distressed at seeing a 10-per-cent saving in production costs squandered many times over by a greatly inflated sales and advertising budget. However, no fundamental improvement can be expected as long as the American public actually prefers ballyhoo to getting its money's worth."

The improvement in American steel production has been due chiefly to pressure from consumers. A contributor "knows of one metallurgist who made his own safety-razor blade, sharpened it, and nitrided it. It has been used daily, without resharpening, for two years. Naturally, razor-blade manufacturers are not interested."

Guns may be made at a greatly increased rate by casting them in molten steel into moulds whirled round at high speed. Change in fashion in metals will increase the production of scrap, and hence decrease primary metal production. Iron and steel will probably not be replaced by aluminium and magnesium for a long time. These light metals are produced by electrolytic analysis, and the relative consumption of power is far greater than in iron-smelting with coal.

The United States metal industry spends only one-hundredth of the money on research per unit of its capital in comparison with the chemical industry. When research is used in this industry as generously as in the chemical industry, remarkable results may be anticipated.

The scope for housing construction in the United States is great. Four million American families are without running

water, indoor closets and baths. One-third to one-half of the families in America cannot afford modern houses. Houses could be made in parts in the factory and assembled on the site.

The possibility for construction is immense. Through the assistance of modern machinery, men may build nearly two thousand times more quickly than the ancient Egyptians. The construction of the Great Pyramid required two million man-years of labour. The Boulder Dam, which is of equal volume, required only two thousand four hundred man-years.

What effects have these, and a thousand other developments, had on employment? Formerly a man worked 3,000 hours in a year, latterly he worked 2,000. If production and employment were represented by the index number of 100 in 1920, the figures for 1935 were 114 and 82. The productivity of the worker in 1935 was 39 per cent higher. An increase of 16 per cent in total employment occurred between 1920 and 1929, but towards this the basic industries of agriculture, mining, manufacture, construction, transportation, communication and public utilities contributed an increase of only 3 per cent. The main contribution came from the service industries of trade, and professional, public, personal and domestic service, in which the increase was 50 per cent.

A large part of the increase in productivity after 1932 was attributable to new processes which had been known for some time but had not previously been introduced owing to lack of confidence on the part of investors of capital.

The total employment in the basic industries fell from an index number of 100 in 1920 to 77.4 in 1935. The biggest falls occurred in construction and railway employment. These fell from 8.5 per cent to 6 per cent and 10.2 per cent to 7.0 per cent of the respective totals of employment in two years. There was only one big rise. This was in transportation other than steam railways, the percentage rising from 6.3 in 1920 to 9.2 in 1935.

It was found that "under the prosperous conditions between

1923 and 1929 one individual worker out of twenty was forced, every two years, to seek employment in a new manufacturing industry, or in a non-manufacturing industry. These conditions placed lighter demands upon industry for the training of new men, but placed much heavier demands upon wage-earners, and enforced a degree of adaptability not required under pre-war conditions."

When men were discharged from factories owing to the discontinuation of a particular process, two-thirds to three-quarters received lower wages when they found a new job, and most of the remainder were unemployed for a long period. E. W. Bakke found that "apparently the qualities which helped men to rise to skilled jobs and high wages *while at work* are of limited use in helping men to readjust satisfactorily *when the job goes*."

The growth in total output from 1920 to 1929 was not sufficient to create enough new jobs to absorb the available man-power, and it may be expected that technological progress will continue to present serious problems of industrial, economic and social readjustment unless some improved methods of solving them are found.

The American investigators did not halt after they had collected some of the facts of recent development. They discussed how the main lines of future development might be forecast. The history of nineteen major inventions was analyzed, and it was found that the average interval between the proposal of the idea and the first patent granted in connection with it was 176 years. The average interval between the first patent and practical use was 24 years. Then from practical use to commercial success 14 years, and to important use 12 more years; or about fifty years from the first serious work on the invention. It is hardly possible to find an invention that became important in less than ten years from the time that it or some fully equivalent substitute was worked on. These figures provide an excellent guide to prediction, for they show that many

inventions that will become of major importance in the future are already in existence, and some of them should be recognizable by intelligent study. Events have shown that a forecast of future technical developments published in 1920 gave a reasonably clear-sighted view, at any rate up to 1936. Of sixty-five inventions predicted in this article, 38 per cent have already been verified, 20 per cent will nearly certainly be verified, 8 per cent proved wrong, and 22 per cent were doubtful. Ultimately, 78 per cent of the predictions will probably be verified and 22 per cent will prove wrong.

It was found that distinguished scientific and technical men make the best predictions in their own field, but they are liable to overlook the possibility of problems in their own field being solved by innovations in other fields. For instance, the control of organisms depends on nerves and hormones. A nerve physiologist will attempt to forecast the explanation of a particular type of behaviour entirely in terms of nervous action, while research by chemical physiologists in an independent field will show that this type of behaviour is in fact due more to hormones than nervous impulses.

There is no reason "why one should not use science in estimating the future, as in any other business." General prophecy has not hitherto been written in a scientific manner, but it should yield valuable knowledge if special students trained in the history of technology would work on it systematically.

The telephone, the motorcar, the airplane, the motion picture, rayon and the radio are now the basis of six major industries which did not exist in 1900, and yet most of the basic inventions had already been made. It should not have been impossible in 1900 to have made a useful forecast of the rise of these industries, and to have prepared social legislation to meet their effects. Wider main roads might easily have been planned. The effects of rayon in undermining class distinction by removing the differences between the styles worn by different classes might have been foreseen. The swift expansion of urban

life through the motorcar should have been plainly visible, and suitable laws for regulating it might have been made, before the rise in estate values made improvements prohibitively expensive.

Will invention continue at the same rate? Some 1,400,000 patents are registered in the United States, and additions to them are made at the rate of 50,000 a year. It is reasonable to suppose that several inventions exist today in an undeveloped state which will have effects as great as the six already mentioned. For instance, the perfection of the cotton-picker would remove the employment of a large part of the negro population of the Southern States. The unemployed labour might flood the North, and the political system of the South would be disorganized.

The general introduction of artificial climate, or air-conditioning, would alter the distribution of population on the earth's surface.

Perfected television will effect enormous changes through propaganda and teaching. The photoelectric cell, or electric eye, sees all that the human eye can see, and more. It does not suffer from fatigue. It brings the automatic factory and the automatic man closer, and it will very probably produce unemployment.

Perhaps the greatest changes are to be expected from the synthesis of substances that have a fundamental rôle in living organisms. Several of the most important natural hormones, such as those which control sexual behaviour, have already been synthesized. These offer the prospects of basic changes in the constitution and nature of man.

Forecasts of the effects of the development of plastics, synthetic rubber, prefabricated houses, facsimile transmission, motorcar trailers, steep-flight airplanes and the intensive cultivation of plants in trays under special chemical and physical conditions would almost certainly provide information of value for far-sighted social legislation.

Some of these inventions, already successful on a small scale, should, according to the experience of the past, be used on a large scale within twenty-six years. Forecasts of their effects, even if only approximate, will prepare man for their arrival, and help him, while it is still easy and before the new interests created by the new inventions have crystallized, to avoid unnecessary social disorganization and draw the maximum benefit from his own achievements.

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79

SCIENCE THWARTED

Up to the year 1850, 74 per cent of all the children born in London died before reaching the age of five. In 1939, the percentage had been reduced to about 12. Deaths from typhoid fever in England declined from 5,000 in 1900 to 206 in 1937. In 1871–80, 2,880 out of every hundred thousand English people were killed each year by tuberculosis. This figure had declined to 690 in 1937. Mortality from scarlet fever sank from 720 per 100,000 in 1871–80 to 9 in 1937. The corresponding figures were 380 and 26 for measles; 510 and 43 for whooping cough. In 1922, 42.5 per cent of all deaths in Britain occurred before the age of fifty. In 1937, the figure had declined to 27 per cent. In the twenty years 1911–31, the average height and weight of boys of twelve attending elementary schools in Leeds had increased by three inches and 10.9 lb. In 1912, 39.5 per cent of the children in the London elementary schools had parasitic skin infections. By 1937, the figure had declined to 2.6 per cent.

These improvements are extraordinary, but they raise the question of what was happening before they were made. A large part of the improvement has been due to the establishment of habits of cleanliness, and another large part, concerning the improvement of physique, to better diet. The better cleanliness and diet are due chiefly to government action and rising wages. The mass of the population has succeeded, largely through political pressure and to a lesser degree through good will, in securing a share of the great increase in production that has accompanied the growth of technology. It enjoys

more soap and food, with the most striking consequences. The explanation why this should have had such great effect has been elucidated by a century of research led by Liebig, Pasteur, the modern students of nutrition and thousands of medical scientists. The outcome of their work has, to some extent, merely confirmed the view of common sense that if men have good wages, they and their families will obtain better food and more soap, fresh air, and sunshine, and will be stronger and healthier.

The provision of unanswerable arguments for policies advocated by reformers has been one of the most valuable results of modern medical research. It is even possible to contend that this service of science has been even more valuable than its entirely new additions to medical knowledge. How can it be decided whether sanitary laws or bacteriological knowledge have been the more beneficial to society? But it is certain that modern knowledge of bacteriology and nutrition has greatly strengthened the demand for better housing and food, and has encouraged a return to what appears to have been to some extent the regimen of the freemen among the ancient Greeks. The results of medical research have been a valuable aid in overcoming the forces that resist social progress. The existence of this conflict implies that the application of medical knowledge is always being resisted by such forces, and when it is not being utilized as it should, the action of these forces may be suspected.

For instance, it has been found that if schoolboys are given additional milk, and butter instead of margarine, the number of fractures in football matches and accidents declines significantly. A large part of hospital work is occupied in treating fractures, and there is no doubt that the amount of it would decrease if the whole population drank more milk and ate more butter.

In 1937 there were 61,339 cases of diphtheria in England and Wales, causing 2,963 deaths. The average child patient stays

in hospital for six weeks, and the annual cost of the disease to the country is £1,500,000. Yet it has been demonstrated that diphtheria can be eliminated. In the town of Hamilton, Ontario, with a population of 155,000, no case of diphtheria has been diagnosed for the past five years, owing to the application of modern measures. In New York City, preventive inoculation has reduced the number of deaths from this disease from 463 in 1929 to 35 in 1936. Nearly all the suffering and waste due to diphtheria could be eliminated at once by preventive inoculation.

The average height and weight of the sons of prosperous Englishmen at the age of eleven are respectively 55.33 inches and 76.22 lb., while those of the working class are respectively 3 inches and 12 lb. less.

The mortality due to tuberculosis is four times as great in the children of the poor under the age of one as in those of the prosperous. The mortality rate for bronchitis and pneumonia is six times as great in the infants of the poor under the age of two.

Mellanby writes that "the day will probably come when the country will regard it as intolerable that the number of deaths of children under two is related to the amount of money received per week by the father of the family." He says that the medical scientist complains of "the great delay which often occurs before many of the teachings, which his investigations have elucidated, are adopted by public authorities and private citizens." He considers that this is due sometimes to administrative inertia, sometimes to lack of political and social interest, and sometimes to laziness, but "more often it is due to such economic and social restrictions as prevent people from attaining the nutritional and hygienic conditions necessary for healthy existence." There is little doubt that it would pay the state to provide milk and other foods free to all school children. The saving through better health and lower incidence of disease would be greater than the cost.

In England the infantile mortality below the age of one year has fallen in the last forty years from 165 per 1,000 to 53 per 1,000, but in New Zealand the figure is now 31 per 1,000. There is no valid reason why the English figure should not be reduced to the New Zealand figure, with an annual saving of the lives of some fifteen thousand English infants every year.

This is the more urgent in view of the decline of population and the destruction of youth in war. There were nearly one million fewer English children up to the age of fourteen in 1931 than in 1921. By 1937, there had been a further fall of 600,000. This was naturally accompanied by a rise in the percentage of the aged. In 1911 there were 1,158 persons over fifty-five years in 100,000 of the population. In 1935 this figure had risen to 1,810. As Mellanby remarks, "It is indeed nature's grimmest joke that medical science is establishing the optimum conditions for safe birth and healthy existence just at the time when fewer and fewer babies are born."

The rapidly increasing number of persons over sixty will have to be supported by an even more rapidly diminishing number of workers under fifty. Mellanby considers that "in spite of the advances in production by machinery and the discoveries of agriculture, there can be little doubt that, assuming the continuance of the existing economic and social system, the present standards of living will only be maintained in the future by harder and more prolonged efforts of the working population."

In spite of the marvellous return on medical research, the British Government spends only £195,000 per annum through its Medical Research Council. It is evident that two of the chief forces thwarting medical science are opposition to higher wages and government expenditure on free foods and inadequate expenditure on research itself.

The contrast between possibility and actuality in technical science is even greater. The millions of discoveries and inventions registered in the United States have not enabled that

country of rich natural resources to eliminate some ten million unemployed, and a vast amount of misery, especially in rural areas.

The conditions which have hindered the rapid adoption of technical improvements in the United States and elsewhere have been studied by Stern. He quotes Clark's observation that in no instance did any one of the patentees created by Queen Elizabeth secure a second patent for an improvement after he had already received one.

The development of the high-pressure steam engine was delayed for many years by James Watt and his partners, who possessed the patents for the low-pressure engine. But Watt's opposition was not without some theoretical basis. He considered that mechanical engineering was not sufficiently advanced to make high-pressure machinery safe, and he feared that a series of serious accidents might lead to legislation against steam engines in general. He appreciated the strength of conservative opposition to technical innovation and believed that a cautious conquest would serve the advance of technology better than a direct attack on the whole front. He was conscious of the attitude of the landed gentlemen and said that they treated "us poor mechanics no better than the slaves who cultivate their vineyards." His cautious attitude was also connected with his melancholy temperament, which prompted him to anticipate that everything would always go wrong.

The tendencies exhibited even by Boulton & Watt have been noticed in the great technological companies that have succeeded theirs. Brandeis, in his testimony on American patents, contended in 1912 that the "great organizations are constitutionally unprogressive. They will not take on the big thing. Take the gas companies of this country; they would not touch the electric light. Take the telegraph company, the Western Union Telegraph Company, they would not touch the telephone. Neither the telephone company nor the telegraph company would touch wireless telegraphy. Now, you would have

supposed that in each of these instances those concerns if they had the ordinary progressiveness of Americans would have said at once, 'We ought to go forward and develop this.' But they turned it down, and it was necessary in each one of those instances, in order to promote those great and revolutionizing inventions, to take entirely new capital."

The United States Steel Corporation was particularly conservative. It "originally ignored or rejected the utilization of Gray's invention of a structural section that could be rolled together in one piece; Tytus' method of manufacturing steel sheets by a continuous process; Gayley's method of supplying a dry blast to blast furnaces; and the centrifugal process of casting ingots which eliminates ingot molds, soaking pits, and blooming mills."

During prosperous periods corporations tend to invest large sums in plant to supply the vigorous demand. When prosperity is followed by depression, there is not enough business to use the expanded plant, so, from the corporation's point of view, there is no point in modernizing the plant with the new inventions developed since the slump in its research laboratory. Thus a corporation may be piling up discoveries that are not being introduced into practice, and the plant in the country where the new inventions are being developed may fall out of date, while backward countries that did not modernize their plants during the prosperous period may begin to introduce the new inventions first.

The coaxial cable, which will transmit hundreds of messages simultaneously, has been introduced more extensively in England than in the country where it was developed, as the former English equipment was more out-of-date, and therefore the obsolescence costs were less than they would have been in the country which had relatively recently extended its equipment, which was then up-to-date but had rapidly been superseded.

The influence of the great concentration of research on electrical communication, described in an earlier section, is not

restricted to the advancement of knowledge. The Bell System owned and controlled 9,234 patents in 1934, of which 4,225 were in use. When asked by the Federal Communications Commission to explain why 5,009 of its patents were not in use, the Company stated that the development of 608 was incomplete, the practical application of 237 depended on the progress of other developments, 660 were awaiting commercial application, superior alternatives were available for 2,126, and there was no public necessity for the use of 1,307. The Federal Communications Commission expressed the opinion that "the determination by the holder or owner of a patent, that there is no public necessity for the device or method covered by the patent, represents in itself patent suppression or patent shelving."

As for the group of 2,126 patents classified as unused because of the availability of superior alternatives, the Commission expressed the opinion that "this is a type of patent-shelving or patent-suppression which results from excessive patent protection acquired for the purpose of suppressing competition. The Bell System has at all times suppressed competition in wire telephony or telegraphy . . . under its telephone or telephonic appliance patents and this exclusion is extended to patents covering any type of construction. Moreover, the Bell System has added to its telephone and telephonic appliance patents any patent that might be of value to its competitors. This policy resulted in the acquisition of a large number of patents covering alternative devices and methods for which the Bell System had no need."

These are expressions of opinion, and it is very difficult to give absolute proof that the non-utilization of a patent is against the public interest. In any case, a patent is private property in America and, according to the Supreme Court, "it is the privilege of any owner of property to use or not use it, without question of motive." The Supreme Court laid down in 1931 that "if the patent is valid the owner can, of course, prohibit

entirely the manufacture, sale or use" of a patented article during the term of the patent.

Informed discussion of the influence of patents is not easy. Stern has stated in his article on the "Restraints upon the Utilization of Inventions" that the Federal Communications Commission's Report on the Patents Structure of the Bell System, dated February, 1937, "has not been made available for distribution. T. J. Slowie, secretary of the Commission, who attributed this fact to the Commission's limited appropriation, likewise refused the author of this article permission to photostat pages of the report."

Famous inventors have repeatedly asserted that corporations have used their financial power to buy inventions at less than their proper price. Edison said in 1912 that "the long delays and enormous costs incident to the procedure of the courts have been seized upon by capitalists to enable them to acquire inventions for nominal sums that are entirely inadequate to encourage really valuable inventions. The inventor is now a dependent, a hired person to the corporation." The Wright brothers were very secretive about their success with the airplane. They concealed details for five years, and are said to have done so because they believed that they would not have been able to defend their patent with less than $200,000 if it had become known.

As Stern says, it seems that the rights of private property, and hence of patents, "are clearly above the other interests of the community and above the needs of technological progress."

Much industrial research is concerned with the discovery of methods of evading the patents of competitors. Corporations seek for inventions which might embarrass their competitors. If they are owned by small private firms, they may assist these small firms to withstand legal attacks by competing corporations and organize them as a sort of guerillas in commercial warfare conducted with the weapon of patents.

Edison has described how he invented a relay at Jay Gould's

request, based on his discovery that moistened chalk becomes slippery when a current passes through it, to enable the financier to attack on the Stock Exchange the Western Union Company, which held Page's patents covering all forms of electromagnetic relay.

Inventions made in response to such requests have proved of value to science. The Podbielnak apparatus for fractional distillation, which has established a new degree of accuracy in some branches of chemistry and has been an essential aid to many a recent spectacular triumph in the synthesis of biologically important substances, was invented in connection with patent litigation.

Fifty per cent of the corporations insist that their staffs, at the time of hiring, shall assign to them the rights in any relevant inventions made during the period of employment. For instance, in 1935 the Ingersoll-Rand Company required its employees to sign a document which contained the following: "In consideration of one dollar ($1) paid to me by Ingersoll-Rand Co., the receipt whereof by me is hereby acknowledged, and of my employment by that company during such time as may be mutually agreeable to that company and myself, I agree to assign and hereby do assign to said company, its successors and assigns, all my rights to inventions which I have made or conceived or which I may hereafter make or conceive, either solely or jointly with others, in the course of such employment, or with the use of the time, material, or facilities of said company, or relating to any method, substance, article of manufacture, or improvements therein within the scope of the business of that company." The agreement stipulates that the inventor will disclose the invention to the company as soon as practicable. In addition to the contents of the agreement, the company prints comments on them on the same form. It explains that without such an agreement it would be impossible to bring new employees "into free and open relations with those engineers who are regularly assign-

ing inventions to the company." Though it does not promise additional compensation for these inventions, "its policy is to recognize all good service of whatever nature, by proper adjustment of the salaries," etc. But "it is obvious that during this employment a man may acquire many records and data and much confidential information which under no circumstances should be used after the termination of the employment."

The drift of these developments is to make those corporations that control virtually the whole of any industry the sole owners of patents bearing on it, and the sole arbiters of how those patents should be used. As these corporations have, in America, the legal status and rights of a private person, it means that they are not responsible to the American community for the use that they make of their private property in patents, even though those patents may have an essential part in the life of that community. Their rights in their patents are certain, but their services to the American people are determined only by their own will and judgment. This does not necessarily mean that these services are not well performed, but it does mean that the American people have signed away, through their own laws, their control over vital machinery in their social life.

As the policy of technical innovation is virtually in the hands of private companies and persons, technical development tends to be discouraged during periods of receding business. For instance, the purchase of industrial machinery in America in 1932 declined by 74 per cent below the average for the years 1919–29.

The effect on technological development of corporations that follow their own interests is seen in the events at Jarrow in England. After the last war British shipbuilding firms could no longer obtain sufficient orders to keep all their shipyards busy. This led to fierce price-cutting competition, so presently many firms combined and, with the support of the govern-

ment, the Bank of England, and other banks, a syndicate was formed to buy shipyards, so that a sufficient number could be closed, and those left open could make a satisfactory profit. The capacity of shipyards for construction was reduced by one-third, though the approach of a great naval war was evident to many persons of political judgment. The syndicate chose the yards to be closed mainly according to the degree of their financial difficulties. Consequently, some of the best-equipped yards in England, including Palmer's Shipyard at Jarrow, were dismantled. After this had happened, a Mr. Salt attempted to purchase the site for the erection of a large modern steelworks. This proposal was fiercely opposed by the neighbouring firms, who saw that the new plant would undersell the products from their older obsolescent plants. These firms, through their Iron and Steel Federation, and its connection with the Bank of England, made it virtually impossible for him to raise funds for his enterprise. They could also virtually have prevented him from selling his products, if he had succeeded in making them, owing to the Iron and Steel Federation's connections with the Continental Steel Cartel and the power given to it by the government to control prices. Mr. Salt's company would have been compelled to pay into a pool, for the benefit of the older firms, a fine practically equal to the savings effected by his superior equipment. The project for a great new steelworks at Jarrow was killed, though a much smaller works was ultimately allowed. As a writer in the *New Statesman* has remarked: "That the effect of these methods has been to weaken Great Britain for war as well as for peace is abundantly clear. For nineteenth-century capitalism it could at any rate be said that, however ruthless it might be about the social consequences of its actions, it did stimulate production and apply new technical inventions with all the speed it could. But this newer capitalism is the enemy of technical progress. Accepting the limitation of markets, it sets out to entrench itself and its obsolescent methods and equipment—to create

scarcity, and out of scarcity to maintain profits in the interests of a narrow oligarchy of big industrialists and financiers."

Only the effects on technology of the policy of the Iron and Steel Trades Federation at Jarrow have been mentioned so far. Nearly the whole working population of Jarrow, which contained an exceptionally large number of highly skilled men, became unemployed. They could find employment only by migrating with their families—a difficult and slow process.

It is said that a banker once defined invention as that which makes his securities insecure. C. F. Kettering, the director of research to the General Motors Corporation, said in 1927 that "bankers regard research as most dangerous and a thing that makes baking hazardous, due to the rapid changes it brings about in industry." When the American metal industries tried to retrieve their losses in the recent slump by introducing the pre-fabrication of houses in factories, with subsequent erection on sites, they were strenuously opposed by banks, who in 1933 held mortgages on about 58 per cent of the value of all urban real estate in America. They, and other property holders, feared that the introduction of cheap houses would lower the market value of existing buildings.

The progress of science and technology is thwarted by many other social influences and traditions. In England, many people excuse the small expenditure on scientific research on the ground that there is a lack of scientific ability and that additions to present expenditure would merely cause money to be wasted on second- and third-rate men, because the first-rate men already have enough. There are instances of English industrial scientists who have had conspicuous success in America after moderate success in England. The chief difference between their conditions in America and in England consisted of much larger subsidies and equipment for research. Some of these men were unable to make great discoveries with small means, but this did not prove that they could not make great discoveries with big means. Success in research may depend as

much nowadays on the ability to organize a team as on the individual ability of a Faraday, who solved very difficult problems merely by personal effort, without one trained assistant.

There is little doubt that a great deal of English scientific ability of this sort is being thwarted by lack of means. The Germans have made better use of organizing ability in research.

Patent agreements between national corporations covering the whole world are tending to cause all of their important research to be concentrated in laboratories established in one country. This has the effect of removing industrial research of the highest class in their domain from other countries. The populations in these countries have no opportunity for work in this domain, and are unable to acquire the knowledge and experience necessary for original work in it. Such countries must pay royalties on the master patent held by the unofficial world corporation, and have neither the laboratories nor the skill to make the new inventions that will enable them to evade them. This does not apply only to small, poor countries. Some of the richest countries prefer to follow this policy, for it is easier to pay royalties than to discover new things, even though the latter policy is the cheaper in the long run.

The progress of science has been thwarted, besides being stimulated, by war. In the past, the demands of military technique have stimulated the study of dynamics through gunnery and chemistry through the need for gunpowder. The improvement of surgery has owed much to the necessities and experience of war. In recent times, the study of aerodynamics has been encouraged chiefly for military purposes, and big advances in metallurgy have been made in response to the demand for harder alloys for armour plate. Innumerable other instances might be quoted. But it seems probable that modern war is more inhibiting than stimulating to science. For instance, as O. Stewart has pointed out, the speed of the winner of the Schneider Cup in 1914 was 86.8 m.p.h., which was 41 m.p.h. better than the previous year. In 1920, after an interval includ-

ing four years of war, it was only 107.8 m.p.h., or 21 m.p.h. better. In 1926 it was 246.5 m.p.h., or about 135 m.p.h., better. Between 1926 and 1931 the speed rose by another 94 m.p.h. to 340 m.p.h. Thus the rate of progress after the war was about four times that during the war, and yet the expenditure on aviation during the war was about £1,000,000,000, while that in equal periods afterwards was about £250,000,000. A large part of the expenditure both in peace and in war is on the mass production of a few models, but after all allowances there seems no doubt that in peace more fundamental research is done, owing to the absence of overwhelming pressure for big production, with the result that progress is quicker.

The precedence of war over peace interests in the development of the airplane is shown by Handley Page's statement that no serious effort to design airplanes to meet civilian needs was made in England until 1926. Comfort, economy and safety are the chief qualities required to meet these needs, but little attention had been given to them, as military authorities were interested only in performance and did not bother about the cost, for in times of war nations abandon economy when they are frightened.

Civil aviation has also been hindered by the cost of urban airfields. This has prevented the establishment of airfields at accessible places in cities and has much reduced the value of air transport, especially over short distances.

The complexity of modern research is making the progress of science more sensitive to war. Advance occurs nowadays through a hundred simultaneous investigations in all parts of the world. If communications are interrupted, this is alone sufficient to reduce the rate of advance. In addition, apparatus and equipment are growing bigger, and may have to be abandoned if a few key technical men are called for military service. In the past, when important experiments could be made with simple apparatus by one or two men in isolation, such interruption was less disturbing.

No careful analysis of the effect of the war of 1914–18 on delaying the progress of science seems to have been made. But a cursory study of the history of the application of X-rays to the analysis of crystal structure shows how the engagement of W. H. and W. L. Bragg in military duties delayed the development of their subject. They published an extremely brilliant series of papers between 1912 and 1914, and did not resume extensive publication until about 1921.

The most original development in the interval was made by Langmuir in America, while that country was still at peace, in his application of the new concepts of atomic structure to the explanation of the properties of films and surfaces.

The long delay in the acceptance of the theory of relativity, and the stunting effects of this on the development of theoretical physics outside Germany, were largely due to the war.

Rutherford's attempts to disintegrate the atom were slowed down by his engagement in research of military interest. His laboratory in 1914 was the scene of one of the most intense and brilliant efforts in science, through his own work and that of Bohr, Moseley and others. What would it have produced between 1914 and 1919 without interruption and if Moseley had not been killed in Gallipoli in 1915?

The destruction of human ability in war is a commonplace, and it is necessary to think only of the death of Moseley, and the certainty that others of comparable ability in other nations were also destroyed, to realize one way in which war thwarts science.

The persistence of the education of statesmen in the classical and literary tradition is another serious hindrance to science. The British Parliament of six hundred members contains no working scientist, and the British Cabinet in 1939 had no member who showed a statesmanlike interest in science. In this sense, the English were worse off in that year than in 1918, when the late Lord Balfour, who was a former president of the British Association for the Advancement of Science, had been

a member of the Cabinet and had succeeded in stimulating its interest in science.

Damage to science through the disapproval of the political opinions of scientists has occurred in all countries, the most notable recent example being in Germany, where two thousand scholars, including five hundred biologists, chemists, physicists and mathematicians, were dismissed from universities and research laboratories after the Nazis had gained power.

The difficulties experienced by young scientists in England, France and America in gaining professorships if they have unpopular political opinions are well known. They are usually rejected on the ground of being difficult to get on with, if the quality of their scientific work is above question.

In the Soviet Union, some geneticists and others with unapproved opinions have been dismissed, and in some cases even references to their papers, which contained widely-accepted results of research, have been suppressed. But it should also be remembered that the great extension of scientific research by the U.S.S.R. is only fifteen years old, and has been accomplished while the country has been surrounded by relentless enmity. While these cases occurred, the authorities of the Soviet Union had also educated in the elements of science millions of people previously illiterate, and had trained thousands of research scientists besides building numerous splendidly equipped new laboratories, and it is probable that the weight of the extension of science in the U.S.S.R. exceeds that of the suppression of some individuals.

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SCIENCE, ART AND DISCONTINUITY

Planck discovered in 1900 that if he assumed that action does not occur in continuously varying amounts, but in multiples of an elemental quantum, he could explain certain puzzling observed properties of radiation. He regarded his quantum theory more or less as a trick for solving certain problems. He did not consider the philosophical contradictions raised by the theory fundamental, and believed they arose from the limitations of the human intellect, and might present no paradoxes to a superhuman intellect.

The acceptance of quantum properties as a fundamental characteristic of nature is due to Bohr. He has explained in his Faraday Lecture the considerations that prompted him to propose his quantum theory of the atom in 1913. He arrived at Manchester just after Rutherford had proved that the atom behaved as if it consisted of a very small heavy nucleus surrounded by relatively distant revolving electrons, like planets round a sun. This discovery was of immense importance, because it showed that the atom might be conceived not as a virtually formless lump of three-dimensional jelly but as an assemblage of discrete particles that could be treated as mathematical points. Bohr felt that Rutherford's atomic model had brought the ancient philosopher's dream of reducing the interpretation of the laws of nature to pure numbers within sight of realization, and the prospect seemed thrilling with promise. But the first consideration of the new Rutherford model showed that it could not operate according to the laws of Newtonian mechanics. If the electrons revolved round the nucleus in a

manner strictly comparable with the revolution of planets round the sun, they should vary their motion continuously and emit a continuously varying quantity of associated radiation. The atoms should, in fact, be in a continuous flux. This was in flat contradiction to the common facts of nature. The constancy and stability of matter are its most striking features. All atoms of hydrogen are alike, and remain essentially alike in all combinations and in all parts of the universe. Further, the varieties of light emitted by hydrogen atoms are remarkably limited, instead of being infinitely variable as they would be if emitted according to Newtonian laws. The exceedingly strict limits of atomic behaviour show that very selective principles govern the movements of the constituent parts of atoms. Without them, such properties as solidity would be impossible. Bohr therefore searched for some principle by which the movements of the parts of the Rutherford atom might be limited. He found it in Planck's idea of the quantum of action. He postulated that any well-defined change of state of an atom is an elementary process, consisting in a complete transition of the atom from one state to another. While the atom was in one of these states it was absolutely unchangeable. Further, the number of these possible states was defined in terms of Planck's quantum, and was practically very small. The fewness and permanence of states while they existed completely explained the paradoxical stability of matter.

Bohr established discontinuity as the foundation of physics when he made his first postulate in 1913. He subsequently explained that the principle of continuity which underlay Newtonian physics had been derived from the study of the properties of bodies whose size is comparable with that of the observer. Changes in such large bodies are aggregates of very large numbers of small quantum changes, and accordingly have the appearance of being continuous, and may be treated as such for practical purposes. When it became possible to study the motions of very small particles, such as electrons, it was found

that they did not obey the laws that had been derived from the study of large objects. There was no necessary reason why they should.

Thus there were the laws of continuous change for large objects and laws of discontinuous change for small objects.

The concepts of continuous motion, space and time were derived by man through his biological experience, and formed his natural mode for exact description. But when he discovered that the properties of very small objects were not continuous, he found that he could describe natural phenomena unambiguously only at the expense of neglecting the excessively minute, and if he wished to speak with complete accuracy he must always be slightly ambiguous. The Principle of Uncertainty is an expression of this limitation, which arises from the inapplicability of continuous concepts to discontinuous phenomena.

While Bohr was laying down in 1913 his momentous postulate of discontinuity as the basis of the properties of matter, other thinkers in entirely different fields were also invoking discontinuity. T. E. Hulme was compiling notes at about the same time for a critique of humanism. He believed that the fundamental difference between medieval civilization and civilization since the Renaissance consisted of a change in human attitude. In the medieval period, human nature was held to be bad, while after the Renaissance it was held to be good. In the first original sin was held to be real, while in the second it was not. Perfection in the earlier period was therefore sought outside human nature, while in the latter it was sought within human nature. The second attitude was accompanied by the belief in the perfectibility of man, and therefore of a justifiable interest in himself. As man contained the seeds of perfection, he could by attention make himself continuously better. This engendered in him the idea of continuous development and progress. It also made human nature the centre of interest, so that it became the chief subject of literature and art. The first

autobiographies were written, and pictorial art became engaged in the description of the human figure and personality.

Hulme followed Weber in the belief that this growth of interest in the human and the self was one of the bases of the capitalist spirit. He thought that this spirit arose first, and that the economic features of capitalistic society were a consequence of it.

As the medieval attitude was not directed towards the human, the subject of its art was not the human figure. It sought perfection not in the living lines of the human figure, but in geometrical shapes. This was seen particularly well in Byzantine art. The angularities of Byzantine figures were not defects in depictions of the human form, because that was not their primary purpose. The Byzantine artists aimed at the construction of abstractly beautiful geometrical shapes, and used the lines of the human figure merely as a foundation for the drawing. The disposition of the lines of the human figure, which were regarded as trivial because human, were distorted into angular and discontinuous shapes intended to suggest geometrical, non-human perfection. A similar aim was seen in ancient Egyptian sculpture.

Hulme believed that the rise of interest in abstract art that began before 1914 was a sign of the collapse of naturalistic art and of the humanistic attitude associated with it. He thought that it foreshadowed a profound transformation of society in which the dogma of continuous human perfectibility would be abandoned, and the movement of humanism, which had been the feature of history since the Renaissance, would be ended. It would be succeeded by a revival of the belief in the reality of original sin and of the absoluteness of the difference between good and evil. The relativity of humanist thought, which, owing to its belief in the continuous perfectibility of human nature, regarded all conduct as differing in degree but not in kind, would be swept away and replaced by a system

based on a hierarchy of values. These would be absolutely discontinuous, and there would be no possibility of transformation by continuous change from one into another.

Hulme forecast that a renewed belief in original sin would lead to the growth of a new social authoritarianism, as the elements of original sin in human nature could not be controlled without external discipline. He concluded that the use of force in social affairs might be salutary, and he translated and expounded Sorel's *Reflections on Violence*. He became an enthusiastic militarist, and was killed in the war in 1917. Mussolini also drew inspiration from Sorel.

Hulme saw that the difference between absolute values, the existence of absolute discontinuities in reality, was fundamental for his philosophy. He therefore consciously aimed at the rehabilitation of the belief in discontinuity, which had been undermined by the continuity theory of humanism, culminating in the idea of progress and the theory of evolution. The belief in continuity had become so unconscious and strong that "when any fact seems to contradict this principle, we are inclined to deny that the fact really exists. We constantly tend to think that the discontinuities in nature are only *apparent*, and that a fuller investigation would reveal the underlying continuity." But both continuity and discontinuity were required for an objective view of reality. It was urgently necessary to destroy the belief in the universality of continuity and become accustomed to gaps and jumps in nature. It was necessary to relearn how to "look at a *gap* or chasm without shuddering."

It is not difficult to see that, given hierarchies of discontinuous absolute values, those who believe they possess the highest of these values will feel compelled to organize society by force, in accordance with their values. As they believe in the reality of original sin, they will also believe in strong external discipline. They will attempt to organize society in a hierarchy of classes, or a hierarchy of groups within one party, with the

assistance of a powerful police directed by those in possession of the highest values. They will create a society which Hulme would have regarded as religious in contrast with humanist, and which will resemble medieval society, with its original sin and the Inquisition, rather than post-Renaissance society, with its belief in the perfectibility of man and its corollaries of individual freedom and development of personality, which received the most characteristic expression in the works of Rousseau.

Hulme's views contained the essence of the principles of Fascism. It would have been instructive to have seen what policy he would have followed if he had survived 1917. He was conscious of a difficulty in his views. He did not wish to lose the results of modern science, and he was aware that these were a product of the humanist period. He therefore said that "a new anti-humanist ideology could not be a mere revival of mediaevalism. The humanist period has developed an honesty in science, and a certain conception of freedom of thought and action which will remain."

Would he have succeeded in combining science with an anti-humanist ideology, or would he have abandoned anti-humanist ideology, or would he have abandoned science and became a Fascist?

He was perhaps the most penetrating contributor to the philosophy to which that part of Fascism which is not mere gangsterism appeals. He was aware of the incompatibility of modern science with this philosophy, and died before he had resolved or cut it.

The danger of drawing faulty conclusions from the existence of discontinuity has been emphasized by Bohr in his strictures on the misinterpretation of the principles of uncertainty. He regards this principle as an advance in objective knowledge. It is a triumph of rational understanding, and is therefore fundamentally anti-mystical. He finds that the principle of discontinuity leads to a better account of the properties of

matter, though its comprehension requires greater clarity of thought. But the principle is not in conflict with the general scientific attitude evolved in the last three centuries.

It is notable that today Bohr, who is more at home with discontinuity and its implications than any other thinker, is the president of the Society for the Protection of Science and Learning.

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THE NEW INTEREST IN THE SOCIAL RELATIONS OF SCIENCE

Science has necessarily been related to social affairs since it came into existence. This is not a new phenomenon, though a new interest in it has arisen, especially during the last decade.

Sprat and the founders of the Royal Society knew that their advancement of scientific research was a response to a general movement that had become evident at least as early as Edward VI. Though they acknowledged the stimulus they had received from Bacon, they were aware that Bacon himself had not done more than enhance the expression of a movement that preceded him.

When the Royal Society was founded, only about one-fifth of the Fellows were scientists. The rest were men of general learning and intelligence, including some professional men and tradesmen, and statesmen who might assist science through influence. Objections to this mixed membership arose early, and Newton proposed in 1674 "the ejection of all useless Fellows." But no effective move to alter the membership was made for nearly two centuries. This occurred during the first half of the nineteenth century. The Society contained 662 Fellows in 1830, but only 106 had published one paper in the Society's journal, and only 44 more than one. The election of the remaining Fellows could be justified only by their patronage of science, but from 1662 until 1828 no Fellow left any substantial sum for this purpose, and then the first Fellow to do so was not one of the patronic type, but the eminent scientist Wollaston. As Lyons has noted, "It is somewhat remarkable that al-

though the majority of the Fellows had been hitherto elected as being men of substance and in a position to be patrons of science, none of them had ever thought of endowing scientific research in any way."

Wollaston's bequest was a sign of the quickening interest in science, which inspired much criticism of the Royal Society's inert condition. A new activity arose in all branches of knowledge at the beginning of the nineteenth century. As Lyons says, "The industrial revolution which had been steadily developing for some years past had fundamentally modified technical industry, and a similar stimulus was deeply influencing many scientific and technical institutions; the Royal Society also had been modifying many of its old ideas and was to do so much more in the years ahead." The placid old order in the Society "was now being seriously challenged by a number of scientific men in the Society who had realized the active part which science should be playing in the promotion of the industrial reorganization which was already in operation." They believed that the scientific members of the Society should have more control over its administration. The finances of the Society were reorganized between 1831 and 1833 by the treasurer, J. W. Lubbock, who was also a banker. W. R. Grove, an eminent judge and the inventor of the Grove cell, proposed that the number of Fellows elected annually should be limited to fifteen, and to candidates with suitable scientific attainments. This change, which was the most important made in the Society since its foundation in 1662, was passed in 1847. It transformed the Society from an eminent body of men interested in science, containing a minority of research workers, into a body of carefully selected specialists. It was a reflection in scientific affairs of the sub-division of labour and specialization characteristic of the industrial and social development of the time. The annual number of elections was restricted to fifteen from 1848 until 1930, though the number of candidates increased enormously, owing to the expansion of scientific re-

search and the increase in the number of scientists in the interval.

Election to the Society had become intensely competitive in the twentieth century. This circumstance stimulated still further the tendency to specialization, as election was secured more easily by those who confined their work to a narrow field. The Society became a highly professionalized body under these conditions, and the attention of its Fellows was withdrawn more and more from the wider aspects of science. Presently, attention to these aspects was deprecated, and was regarded rather as a disqualification in young candidates. The new tradition, which was a result of the change of 1847, was different from that of the founders of the Society, who were men of affairs besides being scientists. Owing to it, the Royal Society at the beginning of the twentieth century devoted less attention to the social relations of science than at any previous period in its history.

Thus, in England, interest in the social relations of science passed largely from the professionalized scientists to men outside their organizations. The most eminent living English student of these relations is H. G. Wells. He has never been elected a Fellow of the Royal Society, which is a striking illustration of a change in its tradition, for if Wells had lived in the second half of the seventeenth century, it is scarcely conceivable that he would not have been one of its most brilliant members. If the new science could be eloquent through Sprat, what would it have been through Wells? He first treated the implications of science through the medium of scientific fantasy. He made imaginative extensions of current scientific tendencies and gave his extrapolations an unequalled interest and verisimilitude. Many readers learned from these works a sense of the possibilities of science. Wells' predecessors in the prehistoric past had invented magical myths, but none had aimed at, or succeeded in, rooting their myths in the ascertained properties of natural substances. He was the first to give such myths,

which are an essential part of culture, a correct scientific tone. The greatness of this achievement is confirmed by the number of his unsuccessful imitators.

The second medium through which he advanced the study of the social relations of science was his writing on socialism and science. He believed strongly in progress: "On the whole—and nowadays almost steadily—things *get better*." He thought that "in the matter of thoughtless and instinctive cruelty—and that is a very fundamental matter—mankind mends steadily. . . . I believe out of me and the Good Will in me and my kind there comes a regenerate world." He "caught a moment's vision of the coming City of Mankind, of a city more wonderful than all my dreaming, full of life, full of youth, full of the spirit of creation." For him "the fundamental idea upon which Socialism rests is the same fundamental idea as that upon which all real scientific work is carried on." It was the assertion that things are orderly by nature, and may be computed and foreseen. The socialist had just the same faith in the existence of this order, and the knowableness of things, and the power of men through cooperation to overcome chance. "While Science gathers knowledge, Socialism in an entirely harmonious spirit criticizes and develops a general plan of social life. Each seeks to replace disorder by order."

Science and socialism were further in sympathy in the demand they made on men to become less egotistical and isolated. He believed that the chief difference between science in the Middle Ages and in the present lay in its collective character, in which all experiments and discoveries were now published and explained. "In a sense scientific research is a triumph over natural instinct, over that mean instinct that makes men secretive, that makes a man keep knowledge to himself and use it slyly to his own advantage." He advocated socialism because it applied to social and economic relationships the "same high rule of frankness and veracity, the same subordination of purely personal considerations to a common end that science demands in

the field of thought and knowledge." The common enemies of science and socialism were "secrecy, subterfuge and private gain."

The socialist wanted "constructive design," he wanted a complete organization for all those human affairs that were of collective importance. "Our ways of manufacturing a great multitude of necessary things, of getting and distributing food, of conducting all sorts of business, of begetting and rearing children, or permitting diseases to engender and spread are chaotic and undisciplined, so badly done that here is enormous hardship, and there enormous waste, here excess and degeneration, and there privation and death." So, "in place of disorderly individual effort, each man doing what he pleases, the Socialist wants organized effort and a plan." Mankind should not follow "the methods of a mob when it ought to follow the method of an army." But he did not wish this image of a plan to be misleading. The socialist did not plan like an architect who "deals with dead stone and timber," but like a gardener who deals with "living and striving things," and "lays out a garden, so that sweet and seemly things may grow, wide and beautiful vistas open and weeds and foulness disappear."

In such a socialist state "all the reasons the contemporary Trade Unionist finds against extra work and unpaid work will have disappeared." The great industries, such as mining, cotton and iron, would "differ chiefly in the permanence of employment and the systematic evasion of the social hardship caused nowadays by new inventions and economies of method. There will exist throughout the world an organized economic survey, which will continually prepare and revise estimates of the need of iron, coal, cloth and so forth," and eliminate speculation. If men were unemployed through technological innovation, they would be sent "not into the casual wards and colonies," but into "the technical schools to train for some fresh use of their energies." There was little need any longer of sheer toil, and it would be "speedily dispensed with at a thousand points

were human patience not cheaper than good machinery." In the socialist state "every man and woman will be a willing and conscious citizen saturated with the spirit of service, in which scientific research will be at a maximum of vigour and efficiency." It followed without saying from the essential principles of socialism, that if war was necessary, "then every citizen will, as a matter of course, take his part."

He believed that socialism should be advanced along three lines. The "*first*, and most important, is the primary intellectual process . . . in its widest sense it includes all science, literature and invention. . . . *Secondly*, comes the propaganda," which was to make socialist conceptions the "common intellectual property of all intelligent people." Then, "*thirdly*, there is the actual changing of practical things in the direction of the coming Socialized State." This was to be done bit by bit, through penetration among statesmen, trades unionists, philanthropists, etc. He said that "Socialism is a moral and intellectual process . . . only secondarily and incidentally does it sway the world of politics. It is not a political movement. . . . It can never become a political movement." The socialist movement was greater than the political organizations that attempted to realize its ideas. There was a natural antagonism between "the thinker and writer who stand by the scheme and seek to develop and expound it, and the politician who attempts to realize it." The politicians declared that socialism could only be realized through politics, but he answered that socialism "can never be narrowed down to politics." Scientific progress, medical organization, education, artistic production and literature were all aspects of socialism, and they lay apart from "anything one may call—except by sheer violence to language—politics." As socialism was an intellectual and moral thing, "it will never tolerate in its adherents the abnegation of individual thought and invention. It demands devotion to an idea, not devotion to a leader. No addicted follower of so-and-so or of so-and-so can be a good Socialist any more than he can

be a good investigator. Socialism has produced no great leaders at all. . . . Socialism under a great leader, or as a powerfully organized party, would be the end of Socialism." It would no doubt inspire great leaders and parties in the future, but it would always remain greater than all such things. Socialism was not the movement of a class, but of the best elements in every class. Under existing conditions it would draw most of its driving force from the Labour Party.

These views were advocated by Wells in 1908. He placed scientific and literary work first, propaganda second, and political action third in importance in the advance towards socialism and better social conditions. Though he believed that society should, to some extent, be organized like an army, he did not want leaders to be unduly exalted, and he was not anxious that intellectual critics and creators should be too closely controlled by the discipline of such an organized society. He believed that scientists and thinkers should take precedence of politicians. With such views, he tended to become an individual critic and educator, and to withdraw from any part in organized political action.

His next phase as a social writer was in education. His greatest contribution in this field was *The Outline of History*, published in 1919. This was the first comprehensive history for the general reader in which weight was given to the influence of science and technology and historical development was not attributed entirely to the ambition of persons and nations. The history hitherto read by the working classes, and taught in elementary schools, was a popularized form of the history written by scholars in the classical and literary tradition. They found Wells' history, with its flavour of science, a new sort of history, which was not restricted to the actions of statesmen with whom they had no contact, but touched on the industry and modern life with which they were familiar. The book was read avidly, especially by skilled workmen. In 1920, before the post-war slump had begun, sixty workmen in one Sheffield

workshop alone bought copies at two and a half guineas each.

In the same year Lenin, who had led the successful socialist revolution of 1917, was preparing plans of the type advocated by Wells in 1908 for the reorganization of social life on an efficient technical basis. A Commission for Elaborating a Plan for the Governmental Electrification of Russia was founded on his initiative in February, 1921. Some two hundred scientists and engineers were engaged on it, and by December a first draft had been completed. This was the foundation for all the subsequent plans of development in that country. It aimed not only at the restoration and extension of electrical equipment, but also at a careful state plan for the extension of the national economy on the basis of advance technique and electrification. Lenin wrote in 1920 that a discussion of this plan had been placed on the agenda of the Congress of the Soviets, "so that the single economic plan for the restoration of national economy that we have been discussing may be outlined from the technical standpoint. Unless Russia is placed on a different technical level, higher than before, restoration of the national economy and Communism are out of the question. Communism is the Soviet power plus the electrification of the whole country, for without electrification progress in industry is impossible." This first plan, named the Goelro Plan, was projected for a term of ten to fifteen years. It provided for a fresh capital investment of 17,000,000,000 roubles in industry, and a production of 180 to 200 per cent of the 1913 level. It involved the construction of big regional power stations, high-voltage networks, and a better utilization of the power, peat, coal and shale resources of the country. The Goelro Plan was completed within ten years, and was succeeded by the still more ambitious first, second and third Five-Year Plans.

Wells visited Russia in 1921, and Lenin spoke to him enthusiastically on the plan for electrification and development. He returned to England and described Lenin as "the dreamer in the Kremlin." Wells had formerly placed political action as

third in importance to intellectual research and propaganda in the achievement of socialism, which prevented him from fully appreciating the work of Lenin and his associates, who put it first. The success of political action in Russia in starting a planned technological economy suggested that more weight should be given to it. Wells and Lenin agreed that socialism could come only through combined research, propaganda, and political action, but they held contrary views of their order of importance. As the post-war years passed, Wells laid more and more emphasis on research and propaganda, while the growing power of Russia gave an increasingly impressive demonstration of the importance of political action. Through this development, Wells became more and more isolated, and consequently pessimistic, while the new generation of students of the social relations of science and technology paid increasing attention to Russia.

While this development was in progress, many other events were altering men's perspective on the social relations of science. The war of 1914–18 had exposed the scientific and technological inadequacies of the English industrial and military system. Scientists were hastily mobilized from wherever they could be found, and the defects in the utilization of science could no longer be ignored. Before the end of the war, scientists began to organize to secure a better treatment of science and themselves. A memorandum signed by some of the ablest of the young scientists was issued in January, 1918, which stated that "one of the main reasons why science does not occupy its proper place in national life is that scientific workers do not exercise in the political and industrial world an influence commensurate with their importance. It is also widely held that the reason why they do not exercise such influence is that they have not hitherto adopted the form of organization which, in a democratic community, is necessary to obtain it."

This proposal was no doubt influenced by others for the or-

ganization of professional workers that had been made in 1917. It led to the formation of the National Union of Scientific Workers. A branch was immediately formed in Cambridge. It held its first public meeting in the Cavendish Laboratory under the chairmanship of Horace Darwin, and an address was delivered by J. J. Thomson. The first general meeting of the union, which had already acquired a membership of 600, was held in London in October, 1918. A. G. Church was appointed full-time secretary in 1920, and was later elected a Member of Parliament. He was able to bring scientific matters to its notice, and largely through his efforts, backed by the union, the government's annual grant to the universities was increased, university teachers were given direct contact with the Treasury, and the conditions of employment of scientists in the Colonial Service was improved. Church was appointed to represent the government on the East Africa Parliamentary Commission of 1924. He convened a conference on educational and cultural films that led to the foundation of the British Film Institute.

The membership was still small, so the union modified its constitution. It severed its connection with the Trades Union Congress, and under the name of the Association of Scientific Workers made a new appeal for members. The number rose to 1,500 in 1927, but fell to 992 in 1929. The Association was faced with bankruptcy in 1930, and Church relinquished his position as general secretary, becoming parliamentary secretary. Nevertheless, the Association had a large part in a movement made in that year in favour of converting the Science Library at South Kensington into a National Science Library, with a virtually complete collection of world scientific publications.

The depression of 1932 was followed by the resignation of 226 more members. The secretarial management of the Association was conducted voluntarily by B. W. Holman from

1930 until 1935. The Association dissolved its own parliamentary committee after the formation of the general Parliamentary Science Committee in 1933.

The senior membership of the Association fell to 695 in 1935, and then a revival began. This was due to several factors. The economic situation had improved. Many scientists had been shocked by the persecution of scientists in Germany after the Nazis had acquired power in Germany in 1933, and a marked renewal of interest in the social relations of science had begun about 1931. In addition, a new generation of scientists were coming forward, whose views had been formed in the post-war years. They had been much more impressed than the pre-war generation by the need for organized action for the protection of their interests. The organization of the Association was overhauled in 1935, largely under the influence of this new generation of scientists. W. A. Wooster of Cambridge became the honorary secretary, and a new class of student members was formed. The senior membership declined to 513, but the junior membership rapidly increased to 177 by the end of 1935.

In 1938, the Association appointed a physicist, Mrs. R. Fremlin, as organizing secretary. The membership steadily increased, and by 1939 had reached 1,319. Strong branches were developed in various centres, especially at Cambridge, where a number of distinguished scientists gave much assistance.

Members and groups of the Association prepared information for the use of the Parliamentary Science Committee. On its behalf, J. D. Bernal drew up a memorandum on research for this committee, which was transmitted to the Lord President of the Council in 1937. The committee was also furnished with proposals concerning the rebate of income tax on expenditure on research and the improvement of the Patent Office Library. In addition to these activities, the Association has recently organized a number of public lectures and discussions on such subjects as the utilization of science, defence and the responsibilities of the scientist, and the relations of science and

society. It has recently proposed the formation of a national council, independent of government administration and consisting of representative scientific and technical personnel, which should aim at the efficient organization and adequate use of the scientific resources of the country.

The Association of Scientific Workers has had a considerable and increasing influence in spite of its small membership. This is due to the high degree of special knowledge possessed by its members. A small group that really knows what it is talking about cannot be ignored, except by manœuvres which, in a democratic society, are ultimately found out and discredited.

The small membership will undoubtedly increase; it is due to the miscellaneous interests of scientists. Their subjects and conditions vary widely, they are frequently isolated, and they still have much of the tradition of specialization and avoidance of social action already mentioned.

While this series of developments was in progress, there were other parallel movements. R. A. Gregory, the editor of *Nature*, who many years before had been a fellow-student with H. G. Wells under T. H. Huxley and had acquired from that master a broader view of the social relations of science than was common in senior academic circles, gave his distinguished support to all efforts to encourage the study of the implications of science. He extended the recognition of science as a cultural study, especially in education. He explained that apart from its vocational value, it contained instruction which was at least as broadening and humane as any that could be learned from the classics.

Under Gregory's editorship, *Nature* acquired an unrivalled position in the scientific world. This was due to his awareness of the implications of science for social affairs, and the importance of this matter. His journal became the most interesting of its kind because he never allowed science to be treated as if it were isolated from the rest of life. Many editors of

scientific journals wondered what was the explanation of *Nature's* success. It was due to the editor's courage and tact in encouraging sober discussion of controversial questions, which, in science as in other fields, are so often concerned with social implications.

Another movement arose as a reaction against general and post-war pessimism. A notable expression of this pessimism was made by the Bishop of Ripon in 1927 in a sermon delivered in Leeds during the meeting of the British Association for the Advancement of Science. His text was taken from the Psalms, and read: "Surely every man walketh in a vain show: . . . he heapeth up riches, and knoweth not who shall gather them. And now, Lord, what wait I for? My hope is in thee." He said that, amid far and away the greatest triumphs ever won by Man's mind over his environment, we were desperately uneasy about the human future because Man had so little control over himself. In spite of all his new mastery of nature, Man did not seem to be really advancing his own cause. Development of his resources did not spell either development or happiness for himself.

Contemporary Man's wealth of technical means made him subject to the old saying "How hardly shall they that have riches enter into the Kingdom of Heaven." He agreed with Bergson's view, expressed in a lecture on the causes of the war in 1915, that Man's body had in effect gone on growing while his soul had largely stood still, or gone back. Until this disproportion had somehow been rectified, Man could not feel safe. He would remain his own worst enemy and the very greatness of his recent achievement would make his ruin more certain and complete. This fear was not confined to isolated Jeremiahs in the Christian Churches. It was widespread, and it paralyzed the very faculties that alone could fight it, and poisoned the nerve centre of faith. The flux of new scientific theories engendered a certain scepticism, and excluded the formation of a religious world view just when it was most needed.

He thought that the sense of direction had been lost amid all the new discoveries, and wondered how many of the specialists asked themselves where the whole was to be found, and whether they increasingly felt the need of a coordinating philosophy. Unless parallel progress was being made towards moral and spiritual supremacy, could we dare to go on enhancing Man's body without some sure hope of saving his soul? The soul is elevated by elevating the personality, and where can such an influence come from, except personality itself? "We must find some means of putting personality once more into the saddle instead of letting things ride the world to a ruin already visible ahead."

He thought that the Hebrews' greatest gift to mankind was their intense conviction in the personality of God. They had not, like us, had to reconcile their conception of God with what science revealed of the vastness, complexity and apparently total indifference of the universe. But "if our world view could somehow resolve itself back into theirs, we, too, might perhaps become simple believers in a personal God." However much the sciences might for immediate practical purposes eliminate personality, their results only underlined the element omitted as being the heart of their problem. Until personality had been accounted for, the facts had not been wholly faced.

These fears for mankind led him to propose a scientific holiday. "After all we could get on very happily if aviation, wireless, television, and the like advanced no further than at present, disappointing as it would be for those whose life work has lain in such fields. Dare I even suggest, at the risk of being lynched by some of my hearers, that the sum of human happiness outside scientific circles would not necessarily be reduced if for ten years every physical and chemical laboratory were closed and the patient and resourceful energy displayed in them transferred to recovering the lost art of getting on together and finding the formula for making both ends meet in the scale of human life. Much, of course, we should lose by this

universal scientific holiday. We should possibly miss new forms of comfort and convenience, new means of making more money for the few at the cost of less work for the many, and a right curiosity on many points would go unsatisfied for a time. But human happiness would not necessarily suffer."

The holiday would give the non-scientific 99 per cent some chance to assimilate the revolutionary knowledge acquired by the 1 per cent, and the 1 per cent would have leisure to read up one another's works and all might go meanwhile in tardy quest of that wisdom which was other and greater than knowledge. The remaking of Man was more urgent than the problems of the several sciences. In this tragic generation we needed, like the tragic psalmist, to make once more our own the faith in a personal God. The scientist was accustomed to abandon hypotheses at the bidding of new facts, and the new facts of modern life had proved once more that salvation could not be found in the extension of science and the mastery of technical organization, but only in individual acts of repentance and faith.

During the same Leeds meeting, Heisenberg gave his first lecture in England, on the principle of uncertainty, which he had just discovered.

The Bishop of Ripon was then forty-five years old. He had been educated at Harrow School, and had gained a scholarship at Balliol College, and graduated at Oxford with first-class honours in classics and philosophy, and had won many prizes. His able restatement of the feudal doctrine, with its emphasis on personality, deprecation of the value of science, and proposals for halting research, nettled even the narrowest specialists, who joined in the protests of scientists with wider views and began to give more serious consideration to the social implications of science.

The next big stimulus in the English development came from the attendance of a group of Soviet scientists at the International Congress of the History of Science held in London in

1931. The eight Soviet delegates arrived by airplane just before the congress started, without having informed the organizers how much time they would require for their papers. Consequently, they found that they had been allotted ten minutes each. As each had prepared addresses from one to three hours long, there were dynamic consultations as to what could be done. An extra half-day was added to the congress, to be devoted entirely to the Soviet papers. Meanwhile, the delegation, which was led by Bukharin, decided on the heroic task of translating, printing and publishing their papers before the end of the congress, within a week, so that their papers would receive adequate expression and their visit not be in vain.

Translators and printers were engaged, and after one of the most extraordinary weeks of intellectual activity that ever occurred in an Embassy, the proofs were just ready for the Soviet scientists' session. Philosophers and scientists rushed about in rolled-up sleeves, and the diligent translators and printer's boys running with "copy" and proofs were working overtime through most of the nights. This enthusiasm for the history of science was unprecedented. The organizers of the congress were hoping that they could do a little to remove the neglect of their subject. One of the members had pointed out that though science had transformed the modern world, the twelve volumes of the Cambridge Modern History contained no more than fifty pages on it. They would have been glad if they could have brought the schools to take a little more interest in science and its history, and a little less in kings and statesmen. The members of the congress had assembled from twenty countries. A few were active scholars in the history of science, but the majority were amateurs, or elderly scientists who had taken an antiquarian interest in science after they had retired from specialist studies. They discussed the history of science in a leisurely way, as if it were of secondary importance. This heterogeneous congress was astonished by the Russians, who discussed the history of science as if it were a subject of unsurpassed im-

portance. For them, in fact, it was such a subject, for the Soviet planning of science and technology was built on the foundation of what history had to teach on science and technology. The eight Russians had evidently organized their discourses. Each chose a different theme, but all had decided beforehand the sort of opinions, found in the papers of other delegates, that they would oppose. They criticized mechanistic views, especially when expressed by biologists whose specialist work was of the highest distinction, so that in several instances they criticized most vigorously the philosophical views of scientists whose scientific work they most admired.

The enthusiasm and aims of the Russians were highly perplexing to the majority of the members of the congress. Rubinstein had prepared a long address on the Soviet electrical industry, but it was ruled out of order. It dealt with the future rather than the past, and historians were unaccustomed to accepting the future as part of history. The most brilliant paper was delivered by B. Hessen on "The Social and Economic Roots of Newton's *Principia.*" Hessen gave the first concrete example of how science should be interpreted as a product of the life and tendencies of society. Predecessors who had given consideration to the social significance of science were literary historians who were not at home with science, and were unable to recognize with confidence which points in scientific theories were significant for history because they were uncertain which scientific ideas were of crucial importance. They were apt to accept too humbly the opinions of scientific specialists who had given no attention at all to historical matters and were acquainted only with the history of the internal development of their own science. Hessen's demonstration of the depth and range of Newton's dependence on the ideas promulgated by the epoch in which he appeared made a profound impression on some of the younger members of the congress. It transformed the study of the history of science, and out-moded the former conceptions of the subject, which treated it as gov-

erned only by the laws of its internal logical development. Henceforth, no satisfactory history of science could be written without giving adequate attention to the dependence of science on social factors. Hessen's evident technical competence in the handling of scientific ideas subsequently gained for his work the attention of scientists who hitherto had despised historical studies because they were so often written by men without first-hand scientific knowledge.

None of the amateur and professional students of the history of science could think of any comment for opening a discussion on the Russians' enthusiastic and exciting papers. After a pause, a twenty-year-old youth named David Guest drew attention to the significance of their views, stressing especially the historical element in all their philosophical and scientific concepts, and contrasting this with the non-historical concepts employed by Pearson and Russell in their philosophy of science. No other speaker could think of anything more to say. Guest subsequently graduated with first-class honours in philosophy at Cambridge University, and was killed in Spain in 1938, fighting with the International Brigade in defence of the Republican Government.

Since the publication of Hessen's essay, a number of books in which science is discussed and expounded in relation to its social background have been published, some with very great success. The movement, of which Hessen's essay was the most brilliant expression, transformed the history of science from a minor into a major subject. It showed that a knowledge of the history of science was not only of entertaining antiquitarian interest, but was essential for the solution of contemporary social problems due to the unorganized growth of a technological society.

This discovery of the social significance of the history of science strengthened the rising interest in the social relations of science. An event that occurred two months later in 1931 added still further to the rising interest. An economic crisis

arose, following the crisis that had occurred in America in 1929. It was followed by an enormous increase in unemployment and the formation of the National Government. The magnitude of the events is illustrated by the change that occurred in the rate of foreign investment by the United States and England. According to the *Monthly Review* of the Midland Bank, the figures from 1920 to 1939 were:

Year	U.S.A. (in millions of dollars)	U.K. (in millions of pounds sterling)	Year	U.S.A. (in millions of dollars)	U.K. (in millions of pounds sterling)
1920	497	60	1930	908	109
1921	623	116	1931	229	46
1922	764	135	1932	32	29
1923	421	136	1933	12	38
1924	969	134	1934	—	43
1925	1,076	88	1935	48	21
1926	1,125	112	1936	23	26
1927	1,337	139	1937	44	32
1928	1,251	143	1938	35	25
1929	673	94	1939 *	20	17

These figures show that in the post-war period up to 1931 capitalism had expanded its foreign investment in the same manner as in the nineteenth and early twentieth centuries, but with the difference that the United States had taken the lead from the United Kingdom. Then there was an extraordinary break. The system of international finance and development through foreign investment, which had functioned for more than a century, was suddenly interrupted. Up to 1931, the United States gold reserve increased at an average rate of only about $200,000,000 per annum, owing to her large foreign investments, but afterwards, and especially in the five years ending 1938, the gold reserve increased by $7,700,000,000, or $1,540,000,000, per annum. No less than $7,000,000,000

* First six months.

came to the United States from outside. Three-quarters of this sum consisted of the liquidation of American assets abroad, foreign purchases of American securities, and the accumulation of short-term funds in the United States, in about equal proportions. America had become, almost in the twinkling of an eye, the repository of funds that might, "in happier times," have been used "for world reconstruction and development." In the period beginning 1932 and ending 1938, Great Britain's foreign investments contracted, until her lending and absorbing positions balanced. The Midland Bank's *Monthly Review* of July–August, 1939, observed that "a position of something like deadlock is revealed, and the prospects for an early resumption of a strong expansive trend in international affairs can scarcely be described as promising." Great Britain's position might have been improved "by a gradual freeing of the channels of world trade," which would have assisted her to renew her provision of new capital for use abroad. "It might be changed fundamentally and rapidly by an emergence from the era of political uncertainty and tension into conditions favourable to confidence among investors and initiative among entrepreneurs. Neither of these developments, however, is yet in sight."

This break, which began in 1931 and ended in deadlock in 1939, raised new questionings of the value of the modern advances in science and technology. A. Ewing, in his presidential address to the British Association in 1932, enquired whether the Association still gave the community reason to support it. In his youth, some of the spokesmen of science, though not the greatest, had displayed a cocksureness in notable contrast with the spirit of contemporary spokesmen. Admiration was now tempered by criticism, and complacency had given way to doubt, and doubt was passing into alarm. There was a sense of perplexity and frustration, as if man had taken the wrong turning. It was impossible to go back, but how should he proceed? "An old exponent of applied mechanics may be forgiven if he

expresses something of the disillusion with which, now standing aside, he watches the sweeping pageant of discovery and invention in which he used to take unbounded delight. It is impossible not to ask, Whither does this tremendous procession tend? What, after all, is its goal? What its probable influence upon the future of the human race?"

The engineer had given man much wealth and comfort, but his achievements had also produced present burdens and potential tragedy. "Man was ethically unprepared for such a bounty. In the slow evolution of morals he is still unfit for the tremendous responsibility it entails. The command of Nature has been put into his hands before he knows how to command himself."

The development of mechanical production was in great measure depriving man of "one inestimable blessing, the necessity of toil." It was destroying the joy in craftsmanship, and when it filled every country with a glut of competitive commodities, every country attempted to secure its home market by tariff walls. Such were the results of the tyranny of the machine.

"Where shall we look for a remedy?" he asked, and said, "I cannot tell."

Another distinguished engineer, Miles Walker, speaking at the same meeting in 1932, had a different outlook. He said that modern technology, if efficiently employed, would make mankind ten times as wealthy as it is today. The majority of the inhabitants of Europe and America were very poorly supplied with commodities, and scarcely anything at all had been done for the teeming millions of India and China.

The great difference between what was possible and what had been achieved was due to the incompetence of rulers. They were very seldom men of real ability, and were talkers rather than doers. They had not undergone any test to show whether they could arrive at a logical conclusion from a given set of premises. The muddle of the world contrasted strongly with

the efficiency of a management of a great engineering works. He believed that if engineers, among whom he included all scientific men, took a greater part in world management, they would make a greater success of it. "In this world crisis there is a call to the engineer to manage the world."

Walker attributed the colossal unemployment, especially in the United States, where food, raw material and capital were abundant, to the desire for excessive and illegitimate profits. Things were usually sold at three or four times the cost of their production. If prices were based exactly and legitimately on the costs of production, the people who make goods would earn sufficient to be able to buy them. They would consequently make more and buy more, and wealth would increase.

He suggested that the British Government should found a self-supporting colony to be run as an experiment by engineers, scientists and economists, to discover how far it is possible for a community, of, say, one hundred thousand persons, to free itself from the restraints and social errors of modern civilization by the application of the best methods of manufacture and distribution.

Walker desired the British Association to support the application of engineering and scientific methods to social questions, but his proposals were baldly rejected, as involving science and scientists in political affairs.

The presidential address in the following year was delivered by F. G. Hopkins, who opposed the pessimism of Ewing, and supported renewed proposals that the Association should attend to the social implications of science. Hopkins said it seemed to him that apart from war, "science and invention have done little to increase opportunities for the display of the more serious of man's irrational impulses. The worst they do perhaps is to give to clever and predatory souls that keep within the law, the whole world for their depredations, instead of a parish or a country as of yore." It was not within his capacity to say anything of value on the cure of the paradox of poverty

amongst plenty, but he confessed that he saw "more present danger in the case of 'Money versus Man' than danger present or future in that of the 'Machine versus Man.'" He had recently been re-reading Bacon's *New Atlantis*, and he thought that while the organization of Solomon's House had been drafted when its author was too much in the mood of a Lord Chancellor, the conception that the best intellects should be organized for the service of the community contained a valuable suggestion.

The replacement of human labour by machinery was creating the prospect of extended leisure. He was optimistic concerning the probable effects of its increase. He believed that the replacement would impose a new structure on society, though few men of affairs realized that. This new structure could be obtained without revolutionary change if there was "real planning for the future." If civilization escaped its other perils, he would have little fear of the final reign of the machine. "We should not altogether forget the difference in use which can be made of real and ample leisure compared with that possible for very brief leisure associated with fatigue; nor the difference between compulsory toil and spontaneous work." Recent experience had shown that the population of Great Britain, except for a minority, was educable. "Most of us have had a tendency in the past to fear the gift of leisure to the majority. To believe that it may be a great social benefit requires some mental adjustment."

Largely under Hopkins' influence the Association now began to attend to the social implications of science. It would not arrange special discussions on the problem, but it asked speakers to draw attention to the social implications of their special subjects. This led to a series of papers which dealt mainly with the actual and possible benefits to society of new discoveries and inventions. The discussions on Noise and Inland Water Supplies, in view of the drought of 1933–34, led to the appointment of government committees on these problems. The

economist Josiah Stamp was asked to discuss the question, and he gave a lecture at the same meeting entitled, "Must Science Ruin Economic Progress?" He said that the innovations of the previous hundred years had been assisted by four agencies: the great elasticity of the demand for old commodities at reduced prices; the rapid introduction of new things, which absorbed labour released in the manufacture of old things by improved processes; the rise in population created by the increase in produce; and industrially backward countries overseas, which could absorb manufactured commodities. The first agency had become less elastic owing to the rise in the standard of living. A man who has good meals does not buy twice as many if their price is reduced fifty per cent.

The second agency was working more and more in the direction of introducing things which demanded increased leisure for their proper absorption and use.

The third agency was ineffective, as the rise in the standard of living was being accompanied by a tendency of the population to fall. The fourth agency was ineffective because hitherto backward countries were now becoming producers.

Stamp expressed the opinion that a theoretical technique could be worked out for the most profitable rate of absorption of scientific invention, but he did not believe that it could be operated without hopelessly impairing the consumer's individual choice of his demands, and it would require in the operators an exalted view of the perfectibility of social organization and political wisdom. "In the field of international relations and foreign trade, which alone can give full effect to scientific discovery, it demands qualities far beyond anything yet attainable."

He believed that economic life in this generation must pay a heavy price for the ultimate gains of science, unless there were large infusions of social direction and internationalism. This did not mean government by scientific technique, technocracy, or any other *transferred* technique, as the aggregate

of human wills were not regulated by the principles that were so potent in mathematics, chemistry, physics or even biology. He thought that scientific workers might contribute much by entering the social sciences and giving a greater proportion of brilliant minds to this field and planning research in it.

Hopkins was also president of the Royal Society during this period. In his last anniversary address, in 1935, he discussed the increasing interest in the social relations of science and the social responsibilities of scientists. He said that the contribution of science to higher standards of intellectual honesty was often overlooked, and mentioned how much the researches of Darwin and the teaching of Huxley had contributed to this in the last century. Science had also, more than any other influence, established the belief in progress, and substituted a dynamic for a static view of the world. This undermined the depressing belief that man and the social fabric he had made for himself, while so imperfect, were yet incapable of betterment, and was the one excuse for that particular form "of professed otherworldliness which from time to time has been an essential part of narrow religious ideals, but which was surely evil in its almost contemptuous indifference to social wrongs and to the urgent problems of this world."

But the scientist, as scientist, has little opportunity for effective action, and he commonly concludes that he will be most useful to society by continuing his chosen work in its proper environment. It was impossible not to sympathize with this view, as the special endowments needed by the scientist were not those of the politician or missionary. Nevertheless, some method of closing the gap between the outlooks of the publicist and scientist was needed. It was a just claim that in a civilization so largely based on science, the scientist should have more influence on policy than he had hitherto been allowed. He thought that not long ago the gap was wide, but it was lessening now.

The immediate importance of the social relations of science had now been recognized by the highest scientific authorities. The British Association organized a discussion under the chairmanship of Walter Elliot, then Minister of Agriculture, on food and agriculture, and John Orr published the results of his investigations of the nation's food. He showed that half of the British people suffered some degree of under-nourishment. His researches inspired the distribution of free milk to school children by the Government, and reports on nutrition by the League of Nations.

The British Association recognized the new tendencies by electing Stamp as president in 1936. He spoke on the Impact of Science upon Society, and elaborated the four points he had made in his earlier address on the question as to whether science must ruin economic progress. The fluidity of invention and the rigidity of society were increasing simultaneously. He thought that the increasing difficulties of innovation might be reduced by psychological research, which would reveal the laws which govern the change of fashion in human demands. He said that he had observed in his business experience that mind-training gained in one specialty was not usually of particular value when applied to general and social problems. He suggested that more money and effort should be devoted to biological and psychological research, and estimated that at present the expenditure on the natural sciences was about ten times that on the social sciences.

Stamp's presidential address was followed by some vigorous discussions, especially in the educational section. Gregory advocated science as a medium for the inculcation of humane values and instanced the researches of Copernicus and Darwin as providing ideas as great and magnificent as any conceived by man.

Hogben explained that the demand for instruction in science was made by powerful social groups whose prosperity depended on the application of science. He mentioned that John-

son censured Milton for wishing to base education on science, and said that while one might know a man for half his life without being able to estimate his skill in science, his moral and prudential character appeared at once. But today, in the machine age, man was a scientist perpetually, and only a moralist at leisure. The physiological learning of an Orr moved the nation's conscience more than volumes of rhetoric addressed to man's moral and prudential character.

He considered that Stamp had shown himself to be an intransigent individualist. Stamp was willing to agree to some slowing down of the rate of innovation, and appealed for the birth control of scientific knowledge rather than the sacrifice of his individualism. Hogben thought that the younger men of science would not be slow to respond to a revival of the machine-wrecking mentality, and would prefer to scrap an outworn individualism and offer the alternative of making the business man a ward in chancery.

Stamp replied that he did not believe that the progress of invention could be stopped, and he thought that further discussion might lead to a common position.

Daniel Hall said that if scientists did not attend to the degradation of their inventions to use in propaganda and war and other anti-social activities they would soon discover that they were slaves, and when they had become slaves the motive and the fascination of scientific work would disappear. He did not believe that scientific bodies such as the British Association and the Royal Society should conduct an agitation on behalf of scientists against the abuse of science. He thought that the creation of an institute for the investigation of the influence of science on society would be more satisfactory.

The discussions on science and the public welfare were the feature of this meeting, and attracted H. G. Wells, who attended a British Association meeting apparently for the first time in his life.

The British Association also incorporated the British Science Guild. This had been founded after Norman Lockyer's presidential address to the Association in 1903 on the Influence of Brain Power in History. Lockyer wished the Association "to promote the application of scientific method and results to social problems and public affairs," but his proposal was rejected, so the new Guild was formed with this object. After the opinion of scientists on the desirability of this application had changed in recent years, there was no longer any reason why the two societies should not amalgamate. Lockyer was the founder and first editor of *Nature*. He was succeeded by Gregory, who has done so much to further Lockyer's aim.

E. G. Conklin, the president of the American Association for the Advancement of Science, and a delegation of distinguished American scientists attended the British Association's meeting of 1936, and were much impressed by the frank discussion of the social relations of science. The British and the Americans decided to explore the possibilities of collaboration.

While these developments were in progress, Ritchie Calder suggested the formation of a World Association for the Advancement of Science, with collaboration between the British and American associations as an embryonic nucleus. Etienne Gilson, at the Harvard Tercentenary in 1936, had advocated the international organization of scholars, and in 1937 the International Council of Scientific Unions received a proposal from the Royal Academy of Amsterdam that it should appoint a committee to study what coordination could be achieved in the opinions which had been put forward regarding the social responsibilities of science and scientists towards the dangers at present menacing civilization. There were lively differences of opinion as to whether such work lay within the objects of the Council, and the proposal was formally withdrawn in favour of one for a committee limited strictly to scientific activity which would report on the most im-

portant results and the directions of progress in the physical, chemical and biological sciences, with reference to their interconnections and the development of the scientific picture of the world in general and the social significance of the applications of science.

The committee was formed with J. M. Burgers as secretary, and made its first report in 1938. It aimed at the preparation of a 250-page report, to be published in 1940, which would give a list of outstanding developments and new applications of science, the organization of scientific research, summaries of interpretative work on the world picture given by science, and of thought on the social relations of science, with bibliographies on all these subjects. It sought assistance from the leading scientific societies of the world. Many of these appointed correspondents for collecting information, and some considered the appointment of paid research workers for this task. The committee stated that it was guided by the conviction that evolution towards a higher goal could be reached only through loyalty to truth and justice. As these are the foundations of the scientists' work, they should bring their familiarity with them, learned in their own special domains, to the relations of the results of their work to human society. They could not leave the use of science entirely to the judgment of others. Their work for a synthetic view of the position of man in the community and in nature implied that freedom of thought should be promoted and defended against personal and group bias, and against obstructions to investigation and publication of its results. The natural spontaneity of free thought would lead to conflicts, but these must be faced. Life was not developed by the suppression of conflicts, but by understanding and resolving them.

Calder's proposal for a World Association for the Advancement of Science was supported in the United States by Kaempffert. Both advocated the declaration by scientists of their belief in freedom and democracy as bases of science.

The American Association now passed resolutions proposing that it should collaborate with the British Association, and all other societies of the same sort throughout the world, to cooperate not only in advancing science, but also in promoting peace among nations and intellectual freedom in order that science may continue to advance and spread more abundantly its benefits to all mankind. Its secretary was instructed to explore the possibilities of collaborating with British scientists, so that the social problems of science might be attacked by the combined scientific abilities of America and Great Britain.

The American Association reaffirmed the resolution of R. A. Millikan and H. N. Russell that the suppression of independent thought and its free expression is a major crime against civilization. Existing liberties had been won through ages of struggle at enormous cost, and there could be no hope of progress in science, justice or peace, or even of material well-being, if they were seriously impaired or lost. It was their duty to denounce all such actions as intolerable forms of tyranny, and there could be no compromise on this issue, because learning could not endure "half slave and half free." "By our life and training as scientists and by our heritage as Americans we must stand for freedom."

The Royal Society of London and the United States National Academy of Sciences established exchange lectures for the description of the progress of science and of new ideas that might bear fruit and give promise of wide expansion in the future. It was hoped that those exchanges would strengthen international contact and so promote peace. The Royal Society exchanged lecturers with the Kaiser-Wilhelm-Gesellschaft in 1939.

The British Trades Union Congress invited eminent scientists to advise it on industrial problems affected by science. A strong committee was formed.

The British Association in the meanwhile discussed how it

might assist the study of the social relations of science more effectively. It studied reports on this subject at its meeting in 1938, which was attended by the secretary of the American Association, one hundred scientists from North America, and by several leading American scientific journalists.

It was evident that if the British Association did not form an organization for the study of the social relations of science, an independent organization for this purpose would be formed. The Association boldly decided to accept the task, and created its new Division for the Social and International Relations of Science. This was done at the Cambridge meeting in 1938. Cambridge is the finest place in England for holding a scientific conference. Its prestige, beauty and facilities attracted a very large attendance of eminent men from many countries. Many of these spent hours and, in fact, days discussing the problems of the social relations of science. Stamp hurried back from Hitler's entertainments at Nürnberg to take part in the deliberations. No activity of the Association in the present century had inspired so much enthusiasm among diverse personalities. It was hoped that the new division would provide authoritative evidence for the possibility of constructive policies. Many good policies were not supported because the facts in their favour were not known, and the people did not know that they were practicable. It was felt that the new division might have great influence if it could reveal the scientific evidence that would provide an indisputable basis for progressive social policies. Its foundation was the chief feature of an exceptional meeting, and will probably prove of historical importance.

Gregory, who had contributed so much to this development, was elected chairman of the new division, and he visited America in 1938–39 to encourage the formation of a similar division there. The American Association had already organized extensive symposia on Science and Society.

It was hoped that corresponding divisions would be established in France, Scandinavia and the Netherlands.

The British Division held its first meeting in March, 1939, to discuss Milk in its Nutritional and Allied Aspects. Two hundred scientists attended. The first London meeting was held in the Royal Institution, and was addressed by Ernest Barker and others on the Impacts of Science on Society. A meeting was held at Manchester, in collaboration with the Manchester Literary and Philosophical Society, in June, 1939, when H. Levy delivered the Alexander Pedler Memorial Lecture on The Social Relations of Science: A Study of Method.

The division also discussed methods of assisting the international dissemination of science, and supported the Political and Economic Planning Society in its researches on the organization of scientific research in Great Britain.

For the first time in English history a paid research worker was set to investigate exactly how British science is organized and financed. Hitherto it had not been anybody's business to know.

The revolution in attitude between 1932 and 1938 probably saved the British Association. Its utility had been slowly but steadily declining. It had performed an essential service in the nineteenth century as a meeting place of scientists and a platform for the announcement of results of public interest. But the increasing number of societies for chemists, biologists, physicists, etc., reduced the value of the British Association as a medium for contact between specialists. The multiplication of scientific journals, better reporting of scientific discoveries in the press, and the sharper competition in discovery prevented scientists from saving up their most important results for publication at the Association's annual meeting. The average interest of the papers declined, and it was evident that if the Association did not serve the needs

of the present, as it had done when it was founded in 1831, its usefulness would fade away. Instead of following this course, it abandoned the old policy of ignoring the social implications of science, and by its courageous action strengthened the hope for a better world through the more intelligent use of science, and the solution of social problems by the application of scientific method.

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SCIENCE AND THE PRESS

Scientific journalists have done much to stimulate the new interest in the social relations of science. They are founding a new profession, though its principles and status are not yet well defined.

Before they appeared, the articles on science in the press were written almost entirely by professors and others who received their main income from other sources. The majority of these articles fell into two types, providing respectively entertainment and religious reflection. Ray Lankester's articles on Science from an Easy Chair are a famous example of the first type. Articles of the second type have been very prominent in recent years. They were written mainly by scientists who had passed the meridian of their creative power and had decided to amuse themselves and the public and increase their income, or examine their attitude to science and life, in their declining years. They produced remarkable writings, being men of great ability, but their articles necessarily reflected the motives of their composition. Like Faustus, they seemed to say that "Philosophy is odious and obscure, 'Tis magic, magic, that hath ravished me."

The third type of article, whose systematic production started about fifteen years ago, consisted of anonymous reports of the progress of science. In these articles the intrinsic interest of science was placed before the attractions of personal opinion, and they bore a professional rather than an amateur mark. Their aim was different. The famous scientists who had contributed the brilliant occasional articles had also intended to serve the social motive of stimulating public in-

terest in science, though this was not their chief motive. But the new scientific journalists made the service of this social motive their chief aim. They saw that science was the distinguishing feature of modern civilization, and yet its principles and progress were not systematically expounded and followed in the press. This was an extraordinary situation. In England, for instance, the population had risen from ten million in 1800 to forty million in 1900. The increase had been possible only through the development of science. And yet the thirty million were widely ignorant of the knowledge to which their existence was due. The increased number of those educated in literature, classics and politics, like that of the rest of the population, was also attributed to science. This section of the new population created through science was, however, the most ignorant of the basis of its existence.

It was evident that modern civilization could not survive if this situation continued. It could not function if three-quarters of the population had virtually no understanding of the thing upon which its existence was based.

The governors of English society still employed the political ideas and methods evolved in societies that did not use power machinery. The British Parliament contained no working scientist, and its Cabinet still (in 1939) contains no working scientist and is under no compulsion to listen to the advice of scientists.

These features of British government were a reflection of class influence and public opinion. Public opinion was not dissatisfied, because it did not appreciate science better than the statesmen. It was clear that statesmen would not appreciate science and scientific methods more until the public insisted that they should.

Some of those who perceived the situation believed that the better public knowledge of science should come through the improvement of science teaching in schools. This is essential, but is not sufficient. The majority of English children

leave school at the age of fourteen, so they cannot learn much science. Also, science advances, and knowledge ten years old, for instance, on some branches of nutrition may be completely out of date. The minds of many persons do not develop until after fourteen. The best mass training for science is given by industrial processes rather than the elementary school. Many persons quite late in their development acquire a rough grasp of scientific ideas through their work as mechanics, electricians and agriculturalists. Their grasp can be clarified and extended through systematic explicatory articles in the press, and this will assist them to judge whether the affairs of state are being managed with scientific acumen. In particular, it will enable them to judge the quality of a statesman's knowledge of science. It does not need deep knowledge to tell whether proposals advanced under the label of science are genuinely scientific. A rough grasp of scientific method and some knowledge of the latest facts are sufficient to detect many gross errors. Joule rightly said that "the trite proverb that a little knowledge is a dangerous thing, absurd in other cases, is peculiarly so in this. This doctrine of fools would necessarily discountenance any education whatsoever because in passing from ignorance to the highest state of intellectual acquirement a man must be at one time induced with the dreaded little knowledge. The truth is that a little knowledge is a little good and much knowledge is a great good, while ignorance is an unmitigated evil allying us with the beasts that perish."

Maynard Keynes said he did not expect that his popular expositions of economics would make its principles clear to the non-specialist public. But he thought that they would help people to see what these principles looked like and to tell whether the proposals of statesmen seemed consonant with them.

In an issue of *Nature* in October, 1939, it was suggested that the British Government's new Ministry of Information

might include a department for scientific information. The editor said that "this view may seem strange, even amusing, to senior administrators of the old type, trained perhaps thirty years ago in a school of ancient philosophy. It will not seem so strange to their younger colleagues, and not at all strange to the large number of skilled working people who are perhaps the most important class in our community. To many of the latter, science is a thing of high repute, and information and advice given in technical and scientific form (provided that is not too dull) carries special conviction. The nation has particular need of their help, . . . it will receive [it] the more freely if . . . they can be told how and why."

The English governing classes, as typified by the Cabinet, are non-scientific, whereas, as the editor of *Nature* explains, the most important part of the population, the skilled artisans, are roughly scientific. This split with regard to science is but one of the social fissures which will destroy the social structure if they are not removed.

The new science writers included in their aims the encouragement of the scientific interests of the skilled masses, to assist them to secure from governments a more scientific treatment of affairs. They conceived scientific journalism as an essential binder in the structure of modern civilization. Thus, as a proper craft, scientific journalism is social. It demands the steady exposition of the simpler and more important facts, as they are discovered, and avoids the expression of opinions. Yet it gives still more attention to the exposition of the atmosphere of science than of the facts, for the scientific attitude is more important than any particular facts. It describes laboratories and interviews discoverers, so that the public may acquire some idea of the atmosphere and processes of creative scientific discovery rather than hear the armchair dreams of scientists after dinner or in retirement.

This work, which requires the rapid adjustment of the mind to many different subjects, demands the whole time

and intellectual energy of the writer. The scientific journalist of the new type tries by continuous impersonal accounts to create the scientific attitude required to solve present social problems.

The work of even the most brilliant sporadic writers, who necessarily appeal mainly to entertainment and religious reflection, does not contribute very much to this end.

The new scientific journalists have found their work difficult, especially in England. There is not one scientific journalist in England who obtains the whole of his income from writing articles for the press. There is not one British newspaper which employs a journalist to give the whole of his time to science.

The low rate of payment for impersonal work that avoids stunts is one of the causes of the difficulty of systematically reporting science. If the scientific journalist is paid by the article, he will do well if he receives five guineas per thousand words, which is the length of the ordinary newspaper column. It is easy to calculate how much could be earned in a year by a weekly article at this rate. A wide range of subjects would be necessary for variety, and as the newspapers' readers contain experts in every subject, the articles must be reasonably accurate, or they will draw protests to the editor. This sort of correspondence is always unwelcome in newspaper offices.

The political journalist has the advantage of dealing with a subject in which the truth is uncertain, or is a matter of opinion, and he can write hundreds of articles without the danger of palpable error. In science the truth is known, and may usually be found in libraries, so when the scientific journalist makes a mistake he is easily proved wrong. This inhibits his initiative and prevents him from writing many articles which he would undertake if they were less risky.

The difficulty of writing on fifty different subjects in a year with a standard of accuracy that does not excite too

much annoyance among scientific specialists is evident. Yet the rate of payment of scientific articles is not higher than for political articles, which may be written with so much more facility. The difficulty of variety increases with time. Many writers can produce a series of interesting articles for a few weeks, but it requires a special ability to maintain the standard indefinitely after stored knowledge has been exhausted.

The sum earned by the scientific journalist paid on space is not net but gross. The information he uses for his articles may have been suggested or collected during travel. It is not possible to obtain the freshness and information needed in the new scientific journalism without it. So the gross sum may easily be reduced by one-third on account of expenses.

The annual sums received by famous scientists who write special articles, or features, are smaller than is commonly believed. If they write much, the novelty of their matter will soon be lost. Only a few highly paid articles will be commissioned in a year, so the total income from them will not be very large. Some famous scientists do not even ask for a high rate of payment. The leading English authority on a certain branch of science has written an article of two columns in a famous newspaper for a fee of five guineas.

The new scientific journalists regard many of the professors who write such articles as "blacklegs." If an editor can obtain an article from the leading authority for five guineas, he is tempted to prefer it to one from a regular scientific journalist. It is very desirable that the best scientists in the country should write for the press if they have a special aptitude for it, but this should not be allowed to obstruct the development of regular science reporting, which requires far more detailed attention than could be spared by any research worker who is doing his job properly. The number of scientists who have a special aptitude for writing in the press is not large. Many scientists have the specialist's tendency to

write down to the public. This disqualifies contribution to reputable papers as it denotes a lack of respect for their readers. One sometimes hears scientists excusing their newspaper articles by saying that they dashed them off in a railway carriage. This is no compliment to the public.

British newspapers may be roughly divided into two types: the commercial press and the responsible press. The chief aim of the first is to make profits, and of the second to express political interests and influence the government.

The commercial press makes its profits from advertising, and therefore seeks big circulation, which is obtained, among other methods, by supplying exciting news that appeals to the emotions rather than the intellect. Evelyn Waugh defined this sort of news when he wrote: "News is what a chap who doesn't care much about anything wants to read." It is not a very hopeful medium for communicating the progress of science to the wide public.

But perhaps the responsible press is in some ways even worse. It has a small circulation. The chief commercial newspapers have a daily circulation of 2,000,000, whereas the responsible newspapers have a circulation of 50,000 to 200,000. They have little money to spend. But there is a still more serious difficulty. Their editorial staffs consist mainly of men who have graduated with first-class honours in classics or history at the older universities. The majority of this class, though there are notable exceptions, are more stupid about science than the men who drive their cars. The motor-driver has some knowledge of the elements of mechanics and electricity, and it is possible through this to assist him to see what the state must do to make the best use of science. But the first-class classical or historical scholar nearly always believes he *knows* how to manage a scientific civilization before he has begun to *learn* about science and its possibilities. He frequently pushes the consideration of science away from him with a mock humility, saying that he does not under-

stand such things. The Cabinet minister or editor who turns his mind away from science is more inimical to progress in a scientific civilization than a population of quarter-educated mechanics who have at least some inkling of the most potent instrument in their civilization. Men with a literary training have the greatest difficulty in appreciating that experiment is more important than theory. Even scientists tend to forget it unless they are continually reminded of it by a Rutherford.

The situation of the new scientific journalist is better in America than in England. The American people have a better general knowledge of science, owing to the traditional use of labour-saving contrivances and the larger amount of science taught in schools. This knowledge, though often superficial, is widespread and has created a demand for science news. A considerable service has grown up in America during the last fifteen years to provide it. Several of the biggest newspapers and news agencies have men who devote the whole of their time to the reporting of science. These scientific journalists of the new type have recently formed a society named the National Association of Science Writers of America. It has about twenty active members, defined as those who are "employed by individual newspapers, newspaper syndicates or press associations and devote more than half their time in this employment in reporting or preparing articles on science in its various aspects."

Yet even in America there are probably not more than five scientific journalists who devote the whole of their time to science. Nor are the wealthy American newspapers much more generous than the British in their payments. For instance, well-known American scientific journalists sometimes attend scientific meetings in Europe, but there is little evidence that they were sent at their papers' expense, though their editors would think nothing of spending £1,500 a year or much more on the salary and expenses of a political correspondent in a foreign capital.

When it has been realized that modern social and international strife is due to the inability of society, owing to its internal conflicts and lack of knowledge, to utilize science properly, scientific journalists will collaborate in equality of status and resources with political journalists. Their present comparative resources and status are a measure of the degree of fundamental disorder in modern society.

Nevertheless, the history of the new interest in the social relations of science has shown that the new scientific journalists have accomplished something, in spite of their handicaps. This is owing to the size of the social forces set in movement through modern science, which they were among the first to express.

They will accomplish much more if they are given better support. They will gain this mainly through the demands of readers for more science. Progress arises from initiative in both editors and readers and reciprocal action between them, but editors follow their readers more than is commonly believed.

There are two ways of organizing a better service of science news, which should be encouraged together. Those newspaper proprietors who foresee the possibility and importance of a growing interest in science should appoint full-time science editors and reporters. Other wealthy bodies interested in the dissemination of scientific information should create and encourage organizations such as the American Science News Service. These are particularly useful in big countries such as America, where newspapers have a mainly local sale and identical copy may be duplicated in the papers in many different states.

Newspapers in a small country such as England do not find such a service so attractive, as many of them have national circulations and are on sale everywhere. They do not wish to have articles identical with those of their competitors. They would need scientific sub-editors to rewrite the news

provided by the service, to give their articles some exclusiveness. They would tend to ignore the service, though they might be forced by competition to imitate an enterprising paper that began to use it. Some years ago one of the big British commercial papers engaged a scientific journalist and published many articles on science. Its competitors imitated it, but after about six months the fashion was worn out and all of the science writers were dismissed. As these papers are so competitive, they prefer to have exclusive articles, and it is possible that if they began to engage special sub-editors to rewrite material from a science service, their competitiveness might lead them to appoint their own full-time science reporters for collecting original information.

The science information service would be valuable both for its own supply of science news and for inspiring the appointment of more full-time science writers. It would be the most useful aid to the dissemination of science in England at present, because it is the most practicable. The initiative for improvement is hardly to be expected from newspaper proprietors, and will come more probably from constructive social and scientific bodies that perceive its desirability. The most practicable method for such bodies to aid the dissemination of science is to found science news services, though the best method in theory is the formation of a corps of science news writers of high status. When the corps' status has been established, it will attract many brilliant candidates.

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THE SOCIAL RESPONSIBILITIES OF SCIENTISTS

The Royal Society of London has 7,000 names on its register of British scientists. The British Ministry of Labour has 100,000 names on its register of technicians and engineers. The population of Great Britain is 45,000,000. These figures give an impression of the small size of the number of scientists as compared with the rest of the population even in an advanced country.

It is evident that the influence scientists can exert in the community through weight of numbers is negligible. The influence of their small number is not multiplied through wealth, as they do not usually possess large fortunes and are very rarely paid more than £2,000 per annum. Nevertheless, though their numbers and wealth are small, they are exceedingly important, as they provide the new knowledge which is the seed of progress in a productive system based on science. They alone are in contact with the future as it is born. What shall they do if they observe that the community is not making the best use of their essential knowledge, but is moving in directions which will pervert the use of old science, make new science barren, and act as a contraceptive to further discovery?

Loyalty to science, to self-interest, and to the welfare of the community would preclude the majority of scientists from acquiescing in such a drift. Many scientists, when they become aware of such tendencies in modern society, feel tempted to resign from scientific work and enter politics. A few of those who do this may find that they are more effective in their new work and are thereby justified, but more

cease being good scientists and do not become good politicians. The retirement from scientific work is not always made from adequate motives, and is sometimes a disguise for concealing professional failure. Those scientists who have become constructive political leaders have rarely started their political life voluntarily. They have usually found themselves forced into politics against their desire, because they have found that political action was necessary to prevent the wastage of their research. The political excursions of eminent experts on nutrition are an example.

If the competent scientist attempts to remedy the obvious abuses that confront him in the course of his work, he will find himself taking political action soon enough, and his political conduct will be reliable because it will be based on exact knowledge acquired during his expert work. Few will be qualified to contradict him in his own field, because he will be more expert.

Every scientist with social feeling will have experienced a desire to drop the tantalizing ardours of hampered research and devote the whole of his energy to the transformation of a social order that hinders science so much. He may feel, with much justification, that concentration on research is impossible in the shadow of social catastrophe. But this feeling should be resisted. Young scientists who abandon science for politics often prove to be mentally unstable, and after a few years of bohemian agitation become conspicuously conservative. Conduct and opinions that appear to be based purely on moral sentiments are nearly always suspect.

Scientists as a class should be doubly anxious to retain within their ranks all of their members who possess social insight. If all scientists with political understanding resigned from science, the remainder would be left without any social guidance. The scientist who becomes a politician in the narrow sense of the term, unless he has really legitimate grounds, commits the dangerous crime of intellectual treason.

The scientist who abandons professional work is liable to perform two disservices. By failing to remain at the frontier of knowledge, he loses the capacity to appeal to the technical knowledge of his colleagues, and he loses his authority as a scientist with the non-professional public. His colleagues no longer pay so much attention to his political suggestions because they come from an outsider, and the public ignores them because he does not possess conventional scientific authority.

The scientist is confronted with the difficult task of acquiring professional competence and practising political activity. Clerk Maxwell laid down, in his inaugural lecture in 1871 as the first Cavendish Professor of Experimental Physics at Cambridge, that the creation of a sound spirit of criticism should be one of the first duties of the new professor and his colleagues. "We are daily receiving fresh proofs that the popularization of scientific doctrines is producing as great an alteration in the mental state of society as the material applications of science are effecting in its outward life." He noted that the inculcation of "sound dynamical ideas has already effected a great change in the language and thoughts even of those who make no pretensions to science," and he feared that the public might be converted to the most absurd opinions if they were "expressed in language, the sound of which recalls some well-known scientific phrase."

As Clerk Maxwell foresaw, one of the tasks of the scientist is to see that the non-scientific public is not misled in the name of science. The scientist who wishes to be of social use can perform an important service by keeping his scientific knowledge up to date and authoritative, so that he can instantly expose pseudo-scientific doctrines that recall the phrases which describe established scientific truths.

There is reason to believe that Rutherford approved his great predecessor's opinion.

Scientists should attempt to excel in their work for social

as well as personal reasons. They should qualify, as far as they are able, for membership in the appropriate scientific societies, which have much influence on professional policy. If they do not, they will not have their share in this influence. These societies sometimes pursue policies that seem misguided, but this is not a sufficient reason for abandoning them. Associations of executants of a healthy technique always possess elements of vitality, while those of executants of a moribund technique are decadent. The Royal Society of London and the Royal Academy of London provide illustrations.

The Royal Society may be open to criticism, but no one will deny that its last five presidents—Bragg, Hopkins, Rutherford, Sherrington and J. J. Thomson—have made distinguished contributions to culture, and their discoveries would be esteemed highly in any rational form of society. The prestige of the Royal Academy is very much less. Who can recall its last five presidents? Are they known throughout the world wherever creative work is in progress? Scarcely anyone accepts them as the leaders of contemporary artistic expression. As they do not represent the most advanced workers in their own field, it is beyond their power, even if they had the will, to exert a constructive influence on the artistic aspects of social affairs.

The belief that academies of art are necessarily decadent is mistaken. The conventional schools and academies of art were constructive during the Renaissance. The artistic interest and activity was spread widely through the population, and at that time art was a socially healthy technique. The associations of its executants accordingly possessed elements of vitality.

The contemporary superiority of the Royal Society to the Royal Academy is due to the healthier condition of scientific technique in comparison with artistic technique.

The same superior healthiness is noticeable in other comparable societies, for instance in those of science masters as

compared with those of literary masters in schools. The publishers of textbooks and manufacturers of scientific instruments are aware of the keen interest of science masters and their associations in new books and instruments. Their enthusiasm and efficiency, in England certainly, are in notable contrast with those of literary masters.

Scientists who wish to have influence in social affairs should attempt to be prominent members of such professional bodies as the Royal Society, the Science Masters' Association and the Association of Scientific Workers.

Assuming that a scientist is competent in his own work, how should he, as a scientist, engage in social affairs? He may do so in several ways. He should join a professional union for the protection of his interests and working conditions. The medical profession has created powerful organizations of this sort, which especially in the earlier part of their history performed valuable social services, such as propaganda for the establishment by law of qualifications for practice. In England, the Association of Scientific Workers has made some progress, and will probably make more, but it still has only 1,319 members. Scientists have difficulty in organizing because their interests and working conditions are exceptionally varied. For example, the problems and conditions that affect physicists, bacteriologists and plant geneticists are often widely different. In addition, scientists generally live in small scattered groups. A specialist in a small university or industrial laboratory may have no colleagues with similar problems and conditions.

The relative comfort of scientists, especially in academic work, is another factor that inhibits organization. In Britain, a scientist who has just qualified will receive a salary of about £200 per annum, if he secures an academic appointment. His hours of work are flexible, he usually has superiors of definite ability, and he can find some congenial colleagues. His conditions are frequently better than the corresponding ones in industrial research, where he may easily start at a lower

salary, keep regular hours from 9 A.M. to 5.30 P.M., and work under a director who often owes his position to pliability, and sometimes to favouritism, or even nepotism. Academic appointments are, on the whole, made more objectively than business appointments.

A scientist who transfers from academic to industrial work, or from the research to the selling side of a business, is often struck by the lower tone, which makes him feel uncomfortable at first. But he generally becomes used to it, and forgets the difference as he becomes absorbed in the exciting game of outwitting competitors.

The relatively attractive conditions of research work dispose many scientists towards conservatism and indifference. They are apt to ignore external circumstances, because discovery cannot be made without intense concentration. They become detached from external affairs and may lose the faculty of thinking about them. The greater the detachment, the greater the difficulty in returning to ordinary matters, and this increasing difficulty widens the detachment still more.

These circumstances expose the scientist to dangerous influences. His work disposes him to orderly thought and action, and his isolation, comfort, and concentration tend to restrict his experience of affairs. He is apt to be attracted by social proposals that appeal to his habits of orderliness in thought and action and at the same time promise to preserve his superior status and comfort. This particular combination is characteristic of Fascist proposals. The material conditions of scientists contain elements that dispose him to Fascism.

Still other factors that dispose him to acquiesce in dictatorship are his habits of accepting authority in his own work, and his despair at the small number of scientists. How can a handful of scientists resist the ruling authorities?

The immediate economic and class interests of scientists tend to make them fall in with authority. But this is not true of their ultimate interests. The socially conscious scientist

should regard the continuous demonstration of this as one of his most important tasks.

The scientist uses foresight as part of his technique. He is in the habit of imagining consequences in the process of planning experiments. He is more susceptible than the majority of men to the logic of foresight. It is possible to appeal to him with particular force through this habit, and to persuade him to consider the prospects of his work and himself. He may be having quite a good time at present, but what will happen in the future? He may have a tendency towards Fascism. What has happened to science in countries where it is established? Are international affairs drifting into war? Will war be good for science, and if he is already engaged in war, are his services being employed to the best advantage, either for military or civil research? Do the authorities know how to make the best use of science?

Many scientists do not believe there is any close connection between science and society. For instance, they may be spectroscopists or pure mathematicians. They do not believe that the nature of their discoveries would vary according to whether they live in Lhasa or New York. They are not without excuse for their view, because the relations between spectroscopes and pure mathematics and daily life have not been adequately analyzed. Until this has been done, many scientists will deny that such relations exist. The thorough demonstration of these relations is one of the scientist's social tasks.

All scientists know that freedom is one of the essential factors for successful research. Some would say that it is by far the most important. Many believe in freedom for scientists, regarding them as a superior caste, and do not care very much whether others are as free as themselves. In some cases they believe in freedom for scientists and regimentation for others.

Many scientists become conscious of their social tasks only

through threats to freedom. Socially conscious scientists should draw the attention of their colleagues to social movements that tend to repress freedom in thought and experiment, and they should always press for positive extensions of freedom in these directions. This will often involve demands for the better financing and organization of research besides the extension of freedom through social legislation.

Apart from the appeal to the scientist to take social action on behalf of science and himself, there is the appeal to him as an ordinary good citizen. Some scientists will feel moved to support constructive social policies from general humanitarian motives. They will call for the organization of a better life because they are disgusted by unnecessary suffering and inefficiency.

But however scientists take part in social affairs, influence will not flow from numbers and wealth. They might try to secure more power through their special knowledge. If the seven thousand scientists in England went on strike, the life of the country would ultimately be strangled. But its death would not follow immediately. That large part of science whose application has already been reduced to routine would remain in use. Months would pass before the effects became serious, and in that time the majority of scientists would have returned to work under threats. Lea has shown in his history of the Inquisition that the resistance of intellectual workers to persecution has not been notably high.

For all these reasons, scientists cannot achieve much by independent action. These factors have been brought into existence by social forces more powerful than the scientists. They should aim at guiding these forces, which they can influence but cannot control. Their most effective policy is to study the general movement of social affairs, and attach themselves to those major social forces which seem to be most constructive. They can discover these only from political study and

experience, so they must take some part in social affairs in order to discover whom they must support.

They should advocate the dissemination of a better knowledge of science throughout the population, so that politicians must acquire a grounding of scientific knowledge before they can satisfy the electorate. They should not propose government by scientists. As soon as a scientist becomes a politician, under present conditions, he ceases to be a working scientist and his methods become indistinguishable from those of any other politician. He is apt to forget all about science in his struggle to secure Cabinet rank. When a politician is devoting sixteen hours every day to the achievement of a higher position, he will not think about science unless he perceives that this will gratify a powerful section of the population.

The social responsibilities of scientists seem, then, to include the following:

1. The exposure of errors in science, such as racialist theories, and the exposure of scientific errors in the ideas of destructive social movements.

2. The organization of such intellectual criticism by cooperative effort, so that sober fact will not be borne down by blatancy and persistence.

3. Solid demonstrations of the relations between science and social affairs, so that scientists may be convinced of the need for their taking part collectively in social affairs, for the sake of science.

4. Descriptions of what social improvements are desirable for the advancement of science, and explanations of how science is thwarted in bad social systems, and how this thwarting is liable to produce still worse social systems. This would include accounts of how science has declined in Fascist countries.

5. The persuasion of scientists who keep their scientific and political ideas in separate compartments to support constructive movements on the ordinary political grounds of economic interest and social justice.

6. The collective establishment of contacts with Cabinets and centres of government, so that no major political decision can

be taken in ignorance of relevant scientific knowledge. They should destroy the conception of scientists as the servants of politicians, but they should not become politicians. They should see only that politicians and the electorate are permeated by science, so that action contrary to the indications of scientific knowledge would become difficult or impossible.

7. In peace, to cooperate with all constructive social and intellectual movements, expand science, and remove the causes of war.

8. In war, to consider which side is the less inimical to science, and then do what is possible to see that it is not defeated. Scientists, like others, cannot be above the battle, either in politics or in war.

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